GEOLOGICAL
ASPECTS OF MINING

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BY

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PREFACE

THE mining engineer, whether primarily interested in coal or in metal mining, is deeply concerned with the science of geology, the study of the earth and the rocks comprising it.

All mines and collieries are wasting assets with limited reserves and ultimately these become exhausted. In the British coal mining industry capacity is being exhausted at the rate of four to five million tons per annum, so that in addition to the increase in annual output projected in *Investing in Coal* which in April, 1956, revised and brought up to date the *Plan for Coal* of the National Coal Board put forward in 1950, this loss of capacity has also to be made good. This has entailed a very extensive programme of prospecting and boring to prove new fields in the concealed areas which is only now being somewhat reduced. The reconstruction and new sinkings projected, however, have underlined how much the period of completion of these projects depends upon the speed of sinking and drifting achieved, and the heavy costs in increased interest on capital and deferred output which any reduction in progress of these operations entails. Great efforts are, therefore, being made to mechanize successfully and to the utmost extent those operations and techniques adopted abroad, particularly in South Africa, which are being tried out in the more difficult conditions of weaker rocks and more stringent regulations applying in this country.

This book deals, therefore, with the science of geology with particular reference to mining operations, with prospecting for minerals, including geophysical methods, with boring for minerals and with means of gaining access to minerals by drifting and sinking.

It is intended for students of mining in the universities and technical colleges taking degrees, Ordinary and Higher National Certificates and Diplomas in Mining and the examinations of the Mining Qualifications Board and for the Associate Membership of the Institution of Mining Engineers.

In addition it is hoped the book will be found useful to others interested in mining, however indirectly.

Several of the illustrations in the first part of the book are from *Coal and the Coalfields in Wales* and *Limestones*, by Dr. F. J. North, D.Sc., F.G.S., by permission of the latter and the National Museum of Wales, to both of whom and to Professor J. G. C. Anderson, for the use of a number of photographs, grateful thanks are due.

CONTENTS

CHAPTER I

INTRODUCTORY

GEOLOGY has been defined as the Science of the Earth. As all the operations with which the mining engineer is concerned are intimately connected with at least the solid part of it, some knowledge of this science is imperative; as for the particular rocks with which the coal-miner is concerned, the acquaintance should be a fairly close one. A little knowledge should not, however, be allowed to become a dangerous thing and when confronted with a very intricate geological problem, where a mistake would involve the loss of thousands of pounds, it is wise to have conclusions "vetted" by an expert. To the coal-mining engineer the Carboniferous system is of the greatest importance but, in the concealed coalfields, shafts will have to pass through newer rocks, so that these are also of interest particularly as the capital cost of equipping a new colliery will be greatly affected by the newer rocks these shafts have to penetrate. The probable course of faults and other troubles which affect coal seams must also receive attention.

The earth is an oblate spheroid with a gaseous envelope or atmosphere composed of a mechanical mixture of gases of which the important are nitrogen 77·91 per cent; oxygen 20·66 per cent, water-vapour, 1·40 per cent, and carbon dioxide 0·03 per cent. The nitrogen content includes small proportions of several inert gases, helium, argon, neon, and traces of nitric oxide and ammonia. The water-vapour content of the atmosphere depends particularly on the temperature. Water vapour is continuously evaporated from oceans, streams and rivers, to be condensed and to fall as rain or snow, in which form it becomes a geological agent of denudation. The atmosphere, in the form of wind, is also a potent agent of denudation, particularly in desert countries where wind sand-blasting and etching may be practically the sole agent of denudation. In addition to winds as such, there is an imperceptible movement of warm air rising and cold air descending and, near the coast, the diurnal land and sea breezes. The drift of cold air from the poles through the rising of heated air in the tropics is acted upon by the rotation of the earth giving a resultant direction from the N.E. in the northern hemisphere. The direction of these prevailing winds, or so-called "trade" winds is, however, complicated by the irregular distribution

of sea and land. High altitude recordings indicate that in the upper atmosphere at a height of six to twenty-five miles a zone of constant minimum temperature at −100°F exists.

The Hydrosphere, or that portion of the earth's surface which is covered with water or ice, amounts to 72 per cent of the surface of the globe. Around the continents is a submerged shelf where the sea floor slopes gradually down to a depth of 100 fathoms and then descends suddenly to much greater depths. It is usual to include the continental shelves, at present temporarily submerged, as part of the continents and the ratio of oceans to land then becomes 2 to 1. As the land areas are characterized by a diversity of plains, valleys, plateaux and mountain chains, so the floor of the oceans are similarly uneven with the deepest portions in long, narrow strips not far removed from the continental shelves. The deepest soundings are approximately the same as the height of the highest peak, Everest, 29,000 ft, but the average ocean depth is about 2,500 fathoms, while the average height of the land above sea-level is 2,000 ft.

Disregarding for the present "combined" water occurring as water of crystallization and water absorbed, two types of "free" water are to be distinguished—fresh water and salt water. The difference is one of degree only, and from a geological point of view is important in that the inhabitants of the two types differ and give an index of the conditions associated with the deposition of the sediments in which their skeletons are buried on death. Thus, the distinction between fresh-water and marine fossils is of importance in correlating deposits in the coal measures as in other formations.

All waters contain some salts in solution and in seawater the amount is not constant but depends upon local conditions, being higher in enclosed areas in the tropics where temperature and evaporation rate is high. The average solids' content is 34 parts per 1,000 parts of water and consists of sodium chloride 78 per cent, magnesium chloride 11 per cent, magnesium sulphate 4·7 per cent, calcium sulphate 3·6 per cent, potassium sulphate 2·5 per cent and magnesium bromide and calcium carbonate together 0·5 per cent. Gases are also dissolved and those of importance are oxygen and carbon dioxide, necessary for the existence of marine animals and plants.

The movements of oceans are of course influenced by the attraction of the sun and moon which give rise to tides. Wind also causes movement of the surface of the water in the form of waves, while differences of temperature give rise to well-established currents such as the Gulf Stream. Motion in the deeps of the oceans is probably small. The solid portion of the Earth is known as the lithosphere.

Its outside crust and those intrusions such as dykes, sills and the outpourings of volcanoes provide evidence of what is below. This is, however, the subject of much speculative reasoning based particularly on the work of seismologists. A solid body, subjected to a sudden shock or stress either of compression or distortion, has vibrations set up within it which produce waves and in a solid these waves are of both compression and distortion. In compression, the molecules move backwards and forwards in the direction of transmission and the waves are known as longitudinal. Waves of distortion cause the molecules to vibrate at right angles to the direction of transmission. Modern seismographs can differentiate between these different wave forms and also detect a third type which travels through the superficial layers of the earth, round its periphery, and has a longer period of vibration than the others. The three distinct types have different speeds of travel and so arrive at a recording station at different times, the longitudinal waves with highest speed arrive first and give the "preliminary tremors" of an earthquake which precede the main shock, compounded of transverse and peripheral waves. The longitudinal and transverse waves travel through the earth but their paths are not straight lines, but, like light rays passing through a lens or from air into water, are refracted or bent when passing through materials of different densities. Further, liquids, while transmitting compression or longitudinal waves, cannot transmit the transverse or distortion waves. By analysis of earthquake tremors along these lines, the following theories of the condition of the Earth have been evolved. The outer crust partly accessible to man at surface and in mine workings, consists of relatively light sedimentary rocks. These are of varying thickness and may be entirely absent, averaging 5,000 ft, but in some regions reaching 60,000 ft in thickness. The next layer or shell is of crystalline siliceous ("acid") granitic rocks with a low density between 2·7 and 2·8, some ten miles and perhaps as much as twenty-five miles in thickness. Below this is a shell of intermediate basaltic ("basic") type between twenty-five and thirty miles thick, followed by a thick shell of much higher density, 3·3 to 3·4, consisting of silicates of ferro-magnesium of the olivine type. This layer would appear to extend about half-way to the centre of the earth, with changes in density at 750 and 1,800 miles between which, it has been suggested, sulphides and oxides of metals predominate with a density averaging 4·3. The central core of the earth, 4,000 miles in diameter, does not transmit transverse waves and has a density of 12. It is therefore pictured as liquid iron or nickel-iron (as are some meteorites) kept liquid by the weight of the material above. The average density of

the earth is therefore in the region of 5; after it had become detached from the sun it condensed to two immiscible liquids, the lighter forming an outside layer which cooled first and solidified round a dense metal core still molten. It would appear, however, that throughout geological time, as recorded by surface rocks and their fossils, the average surface temperature has remained fairly constant although at any point fluctuations have occurred. Some (and how much is not yet known) of the internal heat of the earth is due to the breaking down of uranium and other radio-active elements into other elements. This transmutation of elements and measurement of the resulting helium content of the rocks, is used by geophysicists to estimate the age of the rocks of the different geological systems referred to later. In any case, the loss of internal heat from the centre of the earth at the surface gives an increase in strata temperature as mines are driven deeper into the earth. This rate of increase of temperature with depth is known as the Geothermic Gradient. In the British Isles it averages 1°F for every 63·5 ft increase in depth. This gradient is fairly high compared with other localities, but the gradient is inconsistent and may vary quite widely within a few miles. On the Witwatersrand, it is only 1°F for 254 ft increase of depth and enables mining to take place without artificial cooling down to a depth of 8,000 ft and with artificial cooling to the region of 14,000 ft and perhaps deeper, whereas the limits of mining as at present known are about half these depths in these islands. In Canada and the U.S.A., the average gradient is in the region of 1°F in 100 ft but local steeper gradients occur in volcanic regions, near hot-springs and perhaps where the radio-active mineral content of the rocks is abnormally high. Oil-fields in California and India are delivering crude oil to the surface at temperatures nearly at the boiling-point of water. It has been deduced that the temperature of the intermediate layer of the stony crust is constant at about 650°C.

COMPOSITION OF CRUSTAL ROCKS

Silica predominates in the composition of the rocks to which man has access. Tables I and II, which are summations of analyses of rocks from all over the world, show silica, free or combined as silicates, to account for 59 per cent of the total. The three elements, oxygen, silicon and aluminium together account for 83 per cent, Table I; and from Table II, in which the constituents are given, not as elements, but in the form usual in rock analyses, carbon as the element and combined as CO_2, together, is seen to amount to only 0·04 per cent.

Table I

Element	Percentage Composition by Analyses		
Oxygen	47	75	83 per cent
Silicon	28		
Aluminium	8		
Iron	5		
Calcium	3·5		
Sodium	2·75		
Potassium	2·5		
Magnesium	2·25		
	99·0		

Table II

Element	Percentage Composition by Analyses
SiO_2	59·08
Al_2O_3	15·23
Fe_2O_3	3·10
FeO	3·72
MgO	3·45
CaO	5·10
Na_2O	3·71
K_2O	3·11
TiO_2	1·03
H_2O	1·30
P_2O_5	0·28
CO_2 and C	0·04
Cl	0·04
S	0·05
MnO_2	0·12
	99·36

The remaining elements, of which there are over ninety, together aggregate less than 1 per cent of the total. The composition of the rocks is not of course constant. Local concentrations of one or more elements occur, notably in veins, seams and masses, and render the extraction of the particular element economically possible, the concentration necessary for profitable exploitation of the deposit depending upon the market price of the element, and the cost of working and reducing it.

CHAPTER II

BUILDING OF CONTINENTS

SEDIMENTARY rocks were originally laid down in horizontal sheets or more correctly, lenticles, but only exceptionally are they now found horizontal. They are generally inclined or tilted and are folded, dislocated, or "faulted," and otherwise disturbed from their original flat position. This evidence of past movement, coupled with the ubiquitous evidence of earthquakes and readjustment of crustal rocks, demonstrates that the earth's crust is and always has been in a state of unstable equilibrium even though the cause and method of this readjustment is still uncertain. It is clear, however, that crust adjustment occurs in two phases, sudden and gradual.

Earthquakes are tremors and disturbances which are obvious without instrumental aids, in contradistinction to the slight tremors continually occurring and being recorded at seismological stations. They are of two types—

1. Those which herald volcanic action which may or may not result in an eruption of steam, pumice or lava at the surface.

2. Those unaccompanied by volcanicity and known as dislocation earthquakes. These are due to sudden slipping of rocks in the region of faults and thrust planes and often recur in the same localities, as in the vicinity of the Craven Fault in Lancashire and Yorkshire. The shock is communicated to neighbouring rocks but the actual movement may be only a small fraction of an inch.

Disturbing though these phenomena may be, they are only very minor incidents in a much wider movement which may extend over millions of years.

The division of the surface of the earth into oceans and continents, as at present known, is only one chapter of a much longer and more complicated story. It has already been remarked that round the continents proper is an area in which the depth of the sea does not exceed 100 fathoms. In the same way great areas of land on the edges of the continents, with marine fossils in the sedimentary rocks composing them, have been submerged at recurring periods in the past. There is, therefore, an area of land and shallow sea fringing a continent which alternates between submergence and dry land, the latter composed of strata laid down in comparatively shallow depths. Such an area is known as a shelf area. The true continental areas and

ocean deeps are not, however, interchangeable unless certain speculations such as the "continental drift" theory and the implications of the theory of "isostacy" are established. The true continental areas are composed of areas of very ancient rocks, known as Pre-Cambrian, and these have, throughout the geological eras, remained as units,

FIG. 1. CONTINENTAL SHELF AREA HATCHED, SHOWING RIVER DRAINAGE

have never been submerged and therefore exhibit no marine strata. These areas are known as "*shields*"; examples are the Baltic Shield which includes Finland and Scandinavia, the Canadian in the neighbourhood of Hudson Bay, India and the lower half of Africa and Brazil.

Similarly, the ocean deeps are assumed to be permanent. Western Europe including the British Isles (Fig. 1), is a typical shelf area which has been repeatedly submerged as also is the Malay Archipelago representing the converse of an area now more sea than land.

Earth movements on a large scale have been divided into two

classes, continent building or so-called epeirogeneric and mountain-building called orogenic. The difference between the two is one of scale and of direction of the force producing motion. In the former, the force is vertical and the movement up or down; in the latter, the movement is at a low angle, nearly horizontal, and produces before it an intense folding or puckering. With regard to epeirogeneric movements, it has been established by gravimetric methods, such as pendulum observations, that mountain masses bordering continents are composed of lighter rocks while ocean depths are composed of much denser rocks. In the theory of isostacy this is explained by comparing the ocean deeps and the mountain chains to two limbs of a U-tube filled with liquids of different specific gravities, so that the level of the lighter liquid in its limb stands at a higher level than that in the other limb with the denser liquid. Thus in this theory the continents are pictured as floating on a very viscous denser layer. Reduction of a continent by denudation would lead to increase in elevation and the retreat of the sea, of which there is evidence in river rejuvenation. Conversely, the added weight of an icecap during an ice-age would lead to incursion of the sea with drowned valleys and deposition of marine sediments on what was formerly dry land. Until the exposition of Continental Drift Theory, still in the region of speculation but with influential backing, it had been assumed that the continental "shield" areas, despite fluctuations of level relative to sea-level, had remained substantially in their present relative positions throughout geological time; but various matters, particularly the distribution of certain animals and plants and evidence of past ice caps in the present tropics and tropical plants in the Arctic, are difficult to explain if this assumption and that the equator and the poles have remained in their present positions relative to the continents are correct. The theory that continents have drifted was put forward and supported in particular by Wegener, who stressed the fact that the shapes of the continents can be fitted to each other, particularly South Africa and South America. To turn now to the orogenic movements.

At the edge of the shelf area, the products of erosion of the continent from weathering and the other agents of denudation, transported by streams and rivers, are deposited in the seas in the shallow shelf area, and in order to accommodate the sediment without causing silting up, the sea bed must sink progressively. Should this sinking and rate of sedimentation get out of step, local breaks in the succession of the sediments will occur from silting up and deposition of sediment will take place elsewhere until further settlement occurs. According to the theory of isostacy settlement will occur through the

extra weight of the detritus piling up on the sea bed. In this manner, it has been possible for as much as 40 to 50 thousand feet of relatively shallow water sediments to be deposited as a practically continuous sequence. This nine miles of sediment appears to be about the limit that can be attained and approaches the depth of the siliceous granitic top layer of the earth's crust. Some readjustment and accumulation of stress in the crust itself must accompany such accommodation. Fig. 2 shows diagrammatically such an area of sediment deposition which is known as a geosyncline since the arrangement of the sediments in it must be as in a dish, shallow basin or syncline.

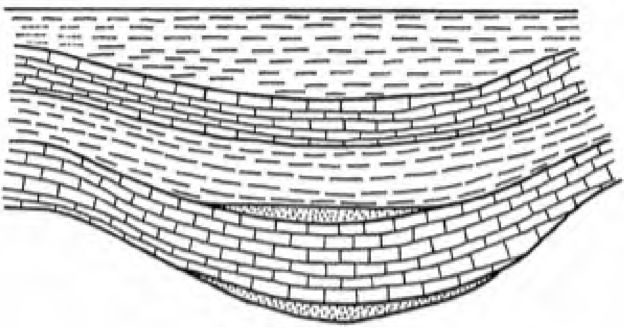


FIG. 2. GEOSYNCLINE

These geosynclines are extremely important as the future sites of mountain chains. They constitute narrow trough-like areas of weakness in the crust. Accumulation may continue tranquilly for perhaps 100 million years, then, as the limit is reached and accumulation of stress becomes excessive, readjustment and relief of stress occurs with folding and faulting of the type known as "*thrusts*," at a low angle, and the production of enormous overfolds called "*nappes*," with the core horizontal. The Alps, Carpathians and the Himalayas have all been formed in this way in what were formerly geosynclinical areas, and huge masses of rock have been driven horizontally 20 miles and more. The Himalayas, for example, were formed comparatively recently and are partly composed of Eocene marine limestones up to 16,000 ft in thickness.

Such mountain chains always consist of long, narrow chains and never square or circular blocks. Again the shallow-water sediments of great thickness in the mountain chains are represented by rocks of the same ages in adjoining areas which are, however, thinner and of different composition. It is interesting to note that on a very minor scale the production of "bumps" and "rockbursts"

with sudden heaving of the floor in coal and metal mines would appear to be the result of similar sudden liberation of accumulated stress through the gradual withdrawal of support by the working away of minerals during exploitation. It would appear that orogenetic epochs occur, that is that mountain building is localized in time as well as situation. In some regions it has never, or only very rarely, occurred in post Pre-Cambrian times, while in others it is restricted to certain periods with long quiescent intervals during which accumulation of detritus and stress occurs to the limit. Successive fold-belts arise alongside previous ones, and in Europe the structure would appear to be the successive addition of strongly folded belts, each to the south of its predecessor, to the Asiatic shield. The same thing has occurred again and again in Britain, and the principle of "posthumous folding" is also well illustrated in these islands. If a sheet of paper is crumpled and straightened out again, then crumpled a second time, it will tend to crumple again along the same folds. This has occurred when Tertiary folds followed the axes of the earlier Armorican folds or Permo-Carboniferous folds.

The reason for the weakness of crust associated with geosynclines can only be surmised. The pressure of the great thickness of sediment probably causes liquefaction and flow of material from beneath the pile, perhaps even of the basaltic layer of the crust. Igneous activity of various kinds commonly accompanies the final stages of mountain-building resulting in lava flows, followed by intrusions of molten igneous material into the cores of anticlines. These may be intrusions from below, or be produced by the fusion and recrystallization *in situ* of the rocks through the terrific pressures to which they are subjected. The substitution of partially compacted sediments to a depth of nine miles in place of granitic, basaltic or thoroughly compacted sedimentary rocks would certainly result, subsequently, in a weakening of the crust in such an area of deposition. These areas have somehow become squeezed between approaching strong blocks of crust and been compelled to bulge up with tremendous crumpling, compression and tension in the folds, resulting in fan and more complicated types. Obviously, the crumpling of a geosyncline, consisting originally of horizontal or very gently dipping strata, by tangential pressure into a fan structure, *a*, or an anticlinorium or series of folds, *b* (Fig. 3), or a nappe of recumbent folds must be accompanied by the shortening of the distance between the edges of the geosyncline. Various estimates of this shortening have been made with very divergent results. Neglecting the effects of radio-active element degradation, cooling of the

earth's interior through loss of heat must produce crumpling of the crust to accommodate the solid crust to the shrinking interior. It has been estimated by geophysical research that this shrinkage, assuming it to occur periodically, should amount to between 50 and 100 miles in each of six major readjustments necessary in the 1,500 million years estimated to have elapsed since Pre-Cambrian times. Of these six postdicted epochs geological evidence has been assembled for four in the British Isles, but the remaining two may be too remote to have left traces sufficiently definite for certainty. The geologist,

FIG. 3. TYPES OF INTENSE FOLDING
(*a*) Fan structure, (*b*) Anticlinorium.

however, would put the accommodation by shortening required at a higher figure of 100 to 200 miles.

To recapitulate, at present geological theory divides the earth's crust into separate entities comprising the ocean basins, the continental shields or blocks, the shelf areas and the geosynclines. The latter are not permanent and may be converted by thrusting into intensely folded long, narrow mountain chains which then form the border of the continental block on to which they are tacked.

THE DIFFERENT TYPES OF ROCKS

A rock has been defined as an aggregate of mineral particles. Hardness and cohesion are immaterial so that a sand and a very hard igneous rock alike come within the definition. Rocks cover a very large range of materials, nearly all inanimate and non-manufactured materials are rocks and the fossilized remains of animate things are also included in the term, notably coal, petroleum and corals.

All the elements are of course encountered in rocks either by themselves, "native," or as compounds with other elements; but the rocks themselves are generally composed of a limited range of minerals. These occur either in the form into which they have crystallized in igneous rocks, or they may have been recrystallized in altered or metamorphic rocks. In bedded or sedimentary rocks, they are mainly derived from the denuded fragments of igneous rocks or older sedimentary rocks, and in pyroclastic rocks, which are

bedded like sedimentary rocks, they are derived from volcanic ashes and tuffs.

Sedimentary Rocks

The sedimentary rocks are generally subdivided into three types—

1. Clastic, that is derived from broken fragments of other rocks. These are further subdivided into arenaceous, composed of sandy or pebbly particles (the latter are sometimes subdivided as "rudaceous"), and "argillaceous," composed of very small particles like clays and muds.
2. Organically formed like some limestones, ironstones, flints, coals and petroleum.
3. Chemically formed including other limestones, ironstone, gypsum and rock salt.

The common rock-forming minerals are shown below.

Mineral	Chemical Compositions
Quartz	SiO_2
Felspars	
(*a*) Orthoclase (acid)	K_2O, Al_2O_3, $6SiO_2$
(*b*) Labradorite (basic)	Na_2O, CaO, $2Al_2O_3$, $8SiO_2$
Micas	
(*a*) Muscovite	K_2O, $3Al_2O_3$, $6SiO_2$, $2H_2O$
(*b*) Biotite	$(HK)_2\,(MgFe)_2(Al,\ Fe_2)(SiO_4)_3$
Amphiboles	
Hornblende	CaO, $3MgFeO$, $4SiO_2$ with Na_2O, Al_2O_3, $4SiO_2$ and $2(MgFe)O$, $2(AlFe_2)O_3$, $2SiO_2$
Pyroxenes	
Augite	$CaMg(SiO_3)_2$ with $(MgFe)(AlFe)_2SiO_6$
Olivine	$2(MgFe)O$, SiO_2
Apatite	$6Ca_3P_2O_8CaF_2$, $CaCl_2$
Fluor Spar	CaF_2
Calcite	$CaCO_3$
Magnetite	Fe_3O_4
Pyrite	FeS_2
Barytes	$BaSO_4$

Some of these are group names of a number of closely related minerals, and one or more examples in each group is given. Most of them are not pure compounds, but are mixed crystals composed of two or more isomorphous substances, that is with the ability to

crystallize in the same form and replace one another in a compound crystal.

Igneous Rocks

These are rocks which have crystallized or solidified from a molten magma. They are largely silicates of various metals and are classed in accordance with their silica content, from 80 per cent in an "acid" rock, such as granite, to 30 per cent in a so-called "basic" rock like basalt. In the acid rocks any free silica crystallizes out as quartz and other common constituents of such rocks are orthoclase felspar and mica. They are generally light coloured and have a relatively low specific gravity of 2·7 to 2·8. In the basic rocks there is a deficiency of silica; and unsaturated felspar-like minerals, called felspathoids, occur together with olivine and basic plagioclase felspar, and in iron-rich magmas, magnetite and ilmenite. They are heavy, with a specific gravity over three and are dark in colour. Midway between these are the intermediate rocks with felspars and alkalis. There are a large number of igneous rocks but it should be realized that many of them are so closely related as to be, for practical purposes, indistinguishable and in fact 90 per cent of these rocks are either granite or basalt.

Being mixtures of minerals the fusion temperatures and order of crystallizing out of the constituents depends on the different eutectic mixtures which may be formed and the conditions under which cooling takes place. The presence of steam and occluded gases also reduces the freezing temperature of the mutually-soluble mixture of silicates. Excess of one constituent will cause that excess to separate out in large crystals, the final eutectic freezing out in a matte of small crystals. The order of crystallizing out is that of decreasing basicity, with non-silica minerals first, then ferro-magnesian silicates and quartz last. The final form of the crystals depends on the rate of cooling and this also determines the division of igneous rocks into—

1. Plutonic or abyssal.
2. Hypabyssal.
3. Volcanic.

The first two are sometimes called intrusive and the third extrusive.

The plutonic rocks are those which have solidified as large, deep-seated masses and have, therefore, cooled slowly owing to the blanketing effect of the rocks round them which have a low thermal conductivity and to the presence in the molten magma of entrapped steam and vapours which further reduce the freezing point of the magma. Common examples are given on the following page.

Acid plutonic rocks—granite.
Intermediate-syenite and diorite.
Basic-gabbro.

The hypabyssal rocks have been cooled more quickly as they have been injected into rocks as laccoliths (Fig. 4), or along the bedding planes of rocks as sills (Figs. 5 and 6A). However, they often cross or "transgress" the beds, as does the Great Whin sill in the north of England, which is intrusive into the Lower Carboniferous over an area of 1,500 square miles and extends into five counties, achieving a maximum thickness of 150 ft. It is obvious that to penetrate over

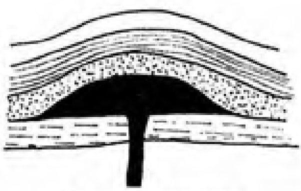


FIG. 4. LACCOLITH

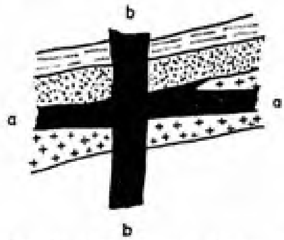


FIG. 5. SILL, *a*, AND DYKE, *b*

such a distance a sheet of such relative thinness must have been extremely labile.

Where the intrusion crosses the bedding planes of the rocks into which it is intruded approximately at right angles, it is known as a "dyke" (Figs. 5*b* and 6A). Both sills and dykes affect the strata and their effect is known as "contact metamorphism" in contra-distinction to the effect of volcanic rocks extruded as lava sheets which affect only the surface below them. The necks of volcanoes also choke with lava which cools slowly and results in a hypabassal rock. Typical hypabyssal rocks are—acid-quartz felsite; intermediate-porphory and porphorite; basic-dolerite. The crystals are much smaller than those of plutonic rocks. Rocks extruded, that is erupted, and spreading as sheets of lava at the surface, cool quickly and form natural glasses with perhaps very small crystals embedded therein. They often exhibit flow structure. Large crystals from magma partly solidified may be erupted and included in the glass and give what is known as a porphoritic structure. Typical lavas are—acid—obsidian and rhyolite; intermediate—trachyte and andesite; basic—basalt. It should be realized that the gradation from coarsely-grained plutonic rock to glassy lava is imperceptible and there is no hard-and-fast division between the three types of igneous rocks, the division being purely arbitrary. From igneous magmas

Fig. 6a. Chalk Covered by and Penetrated by an Igneous Rock, Basalt, Northern Ireland

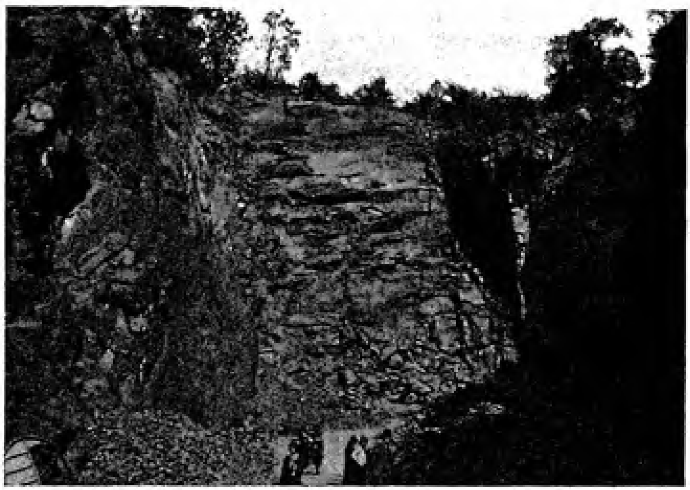


Fig. 6b. Quartz Dolerite Dyke, Quarry at Crosslet, Dumbarton

(J. G. C. Anderson)

gases such as fluorine, boron and sulphur fumes are emitted together with steam. These act upon surrounding rocks causing alteration of constitution and the formation, among other products, of ore deposits. The process is known as pneumatolysis and its effects are of great importance to the metal-mining industries. It is probable also that some of the surrounding or "country" rock is raised to fusion temperature and so adds to the bulk of the magma. This seems likely to occur in the centre of an overfold during orogenetic thrusts.

Metamorphic Rocks

These may be either igneous or sedimentary rocks which have been altered by the effects of heat (thermal) or pressure (dynamic) or a combination of the two. The effect may be local, by contact with plutonic masses, or regional as a result of intense folding, as in the north of Scotland and in the "shield" areas of Canada and the Baltic. The local effects are often the result of ascending gases and steam (pneumatolysis). Metamorphic rocks produced by pressure may be either coarsely crystalline, when they are known as schists, or finely crystalline, when they are called gneisses. They often show a banded appearance and cleavage through movement under pressure and are then said to be "foliated." Those produced by thermal metamorphism are compact, granular and characterized by a speckled appearance. Quartzite from sandstones and marble from limestones are produced by thermal metamorphism, while slates are strictly shales, with an induced cleavage, often at a high angle to the original lamination or division planes between each individual thin layer, which have their origin in the same cause. They are often "puckered" or serrated and ridged.

QUESTIONS

1. Give some account of the theories respecting the composition of the earth between the outer circumference and the centre.
2. Give some account of the phenomena associated with earth movements.
3. Give an account of the principles of the classification of the igneous rocks and show how these are applied to the commoner igneous rocks.
4. What is a geosyncline and what is its importance in the formation of mountain chains?
5. What do you understand by the term orogenesis?
6. What do you understand by the term posthumous folding?
7. What is understood by the term "metamorphism"?

CHAPTER III

THE AGENTS OF DENUDATION

THE breakdown of rocks, both igneous and sedimentary, continues unremittingly and this process of disintegration and decay is known as denudation. The main agents are weathering, gravity, frost, solution by water, erosion by rivers, snow and ice, marine erosion and wind erosion. Climate has much to do with the relative importance of these various agents in any particular region and this in turn is, to a large extent, governed by latitude.

WEATHERING

The minerals of the plutonic rocks have been formed at great depths under pressures of many tons to the square inch and crystallized out over a range of temperature between 400° and 1,400°C and are only in equilibrium under these conditions. On exposure at surface through erosion of the strata previously above them, although harder than most sedimentary rocks, they are readily broken up. Disintegration occurs by the action of water, the atmosphere and alternations of temperature, this combination of chemical and mechanical denuding activity being known as the process of weathering.

As rain falls through the atmosphere it absorbs carbon dioxide and so becomes a dilute acid. On the surface of the earth it may also pick up a further supply of acids from decomposing vegetation and the oxidation of sulphides. Of the minerals composing the igneous rocks, quartz and muscovite mica, characteristic of the acid rocks, are little affected, but the felspars are readily attacked and break down to hydrated compounds of alumina and silica forming a group of very complex "clay minerals" which in a pure form produce kaolin or china clay. In the same conditions pyrites is oxidized and hydrated to final products consisting of hydrated ferric oxide and sulphuric acid. This breakdown of igneous rocks is, of course, the source not only of all sedimentary rocks, but also directly and indirectly, through the subsequent breakdown of these sedimentary rocks, of soils without which vegetation and animal life on this planet could not exist.

The sedimentary rocks are also subject to chemical weathering. A few of them, such as dolomite, gypsum and rock salt, are soluble in water but the presence of dissolved acids greatly increases this

solvent action. Thus the limestones are readily attacked and converted to the more soluble bi-carbonate of calcium.

The sandstones are readily disintegrated by the weathering and solution of the cement between the grains of quartz, mica and other resistant minerals. This cement may be calcium carbonate, iron oxides or silica.

The two former are easily attacked by dilute acids and, coupled with the mechanical weakness of the cements, contribute to the ease of disintegration of these types of sandstones. The colour of sandstones is generally determined by the nature and chemical condition of the cement particularly when this is iron oxide. Sandstones with a cement of silica are harder and more resistant to attack.

The mechanical weathering effect, either daily or seasonal, is due to concentration of stress arising from differential expansion or contraction produced by alternations of heat and cold. Not only may this affect individual crystals in rocks but, particularly if the climate is very dry and the diurnal temperature variation large, it may lead to the bursting of the rock fragments, thus forming scree material of characteristic angular shape, which collects at the foot of cliffs and steep slopes. The effect of gravity, ever present, in moving material from a higher to a lower level, plays, of course, its subsidiary role. The falling material acquires kinetic energy and in turn plays a part in breaking down older material upon which it falls. Landslides and the slow creeping of soil downhill on slopes, although caused primarily by water, needs the assistance of gravity before the separation from the parent mass can take place.

The wedging or riving action of frost and ice depends on the property of water in expanding some ten per cent in passing from the liquid to the solid state. This action, which results in the bursting of rock fragments, is most marked in the colder climates and at high altitudes. In addition, as is very important to agriculture in this country, frost loosens and breaks down surface soils which are left in an open, spongy condition when thawing takes place. This improves the fertility but at the same time renders the soil easily transportable by water.

It is evident that solution by water, particularly when slightly acidulated, must play an important part in the disintegration of rocks. Thus, sandstones may be broken up by removal of the cement between resistant grains, and limestone is dissolved with the formation of gaping fissures (grikes), swallow-holes and huge caverns like the Peak Cavern of Derbyshire. Man has also employed this method for the mining of rock salt in Cheshire and numerous other chemical deposits. The ubiquitous effect of solution could be exemplified at

great length. It is as a transporting and corrading agent, however, that water is perhaps more important. In addition to solution subsequent deposition from solution may occur as in the case of streams traversing wide fissures or emerging from caves or at the surface. As carbon dioxide is released from solution, calcium carbonate becomes less soluble and is deposited in the form of stalactites and stalagmites, or at the surface as deposits of tufa or travertine.

TRANSPORT AND CORRASION BY STREAMS AND RIVERS

The effects of weathering penetrate only a limited depth into the rocks and unless means were available to transport the weathered material away, this would accumulate and shield the rocks below from attack. The commonest agent of transport in temperate regions is water. The efficiency of moving water as a transporting agent depends both upon its volume and its velocity, and the latter depends mainly on the gradient. It may be shown theoretically that the transporting capacity of water depends upon the sixth power of the velocity, although experimentally this is found to be somewhat less and depends also on the friction and shape of the channel. The size of the particles also determines the load, being greater with reduction of grain size. This effect of velocity on transporting power emphasizes the importance of floods in the movement of material. Boulders normally immovable are picked up and rolled along in times of flood. These boulders and larger particles are the main tools of the stream in the performance of its second function, that of corrading or wearing away its bed and breaking down material rolling along its bed by collision between fragments. Material in suspension has little effect in this work and a fully-loaded stream cannot pick up further material without dropping some already being carried, so that corrasion and deposition balance and no further down-cutting takes place. On the other hand a stream with no load does little corrading, so that there is an optimum condition of load at which the maximum rate of corrasion occurs.

Curve of River Erosion

The outlet of a river, at sea-level, is a fixed point and so at a given time is the source. Between the two, erosion proceeds at various rates; at the mouth, it is soon complete; at the source the small volume allows less than average activity; in between the amount depends on the hardness of the rocks and their resistance to abrasive wearing. So the erosion curve of a river in its youthful phase is a

sinuous curve (Fig. 7), flattening towards the mouth. As the river ages, deposition, except in periods of flood, takes place in the hollows where the velocity slackens and erosion proceeds vigorously on the slopes where the velocity is higher until finally the resistant portions are reduced and the gradient is flattened out to a logarithmic curve (Fig. 7), or base-line of river erosion. Simultaneously with the alteration in profile changes occur in the contour of the valley through which the river flows. At first down-cutting is energetic and the valley takes the shape of a sharp-pointed V. But as the river approaches grade, weathering and sub-aerial erosion, in its various

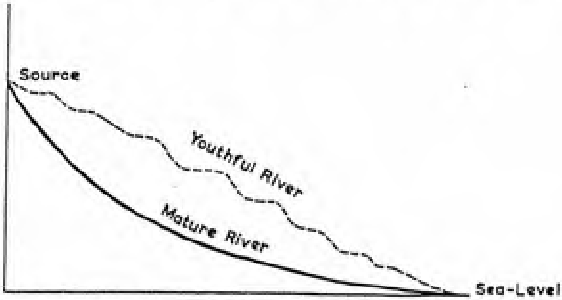


FIG. 7. PROFILE OF YOUTHFUL AND MATURE RIVER SHOWING CONCAVE LOGARITHMIC CURVE OF THE GRADED PROFILE

forms, occurs at a faster rate than that of down-cutting and widening of the valley takes place.

Meanders

Although vertical down-cutting may have finished, the river still possesses energy which is expended in side-cutting. Wherever the course departs from the straight line, through local inequalities of rock hardness, the current sweeps into the outer radius of the curve and this is accentuated by undercutting. The river may meander across its flood plain in this manner and a broad open V valley results with a flat valley floor. On the inside bends of meanders, where the velocity slackens, deposition of sediment, sands and gravels, proceeds and the curve is accentuated (Fig. 8). Finally only a narrow neck of land separates the loops and as the two points, *a*, *a*, are at different levels, a break-through occurs in some period of flood. An ox-bow lake may be formed and the meander thus cut off. Sub-aerial erosion proceeds and as the river changes from maturity to old-age, the contour of the surface drained is worn down to a plain with local low elevations of the most resistant rocks, with

the river meandering across it. This is the end-product of river-erosion and is known as a "Peneplain."

Development of Drainage Systems

When new land is uplifted through earth movement it generally takes the form of an anticline (Fig. 9), or some related more compli-

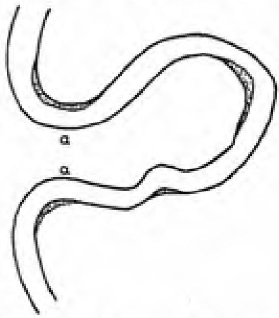


FIG. 8. RIVER MEANDERS SHOWING DEPOSITION OF SEDIMENT ON THE INSIDE OF THE BENDS

cated form. Part of the rain falling on this arch will run off to the dip and the remainder, with the exception of that evaporated back into the atmosphere, will sink into the rocks and re-appear at the spring-line, *s* (Figs. 10 and 11).

Consequent Streams

The axis of the anticline, *aa*, (Fig. 10) forms a watershed or divide and in the ideal, homogeneous rock succession which is postulated,

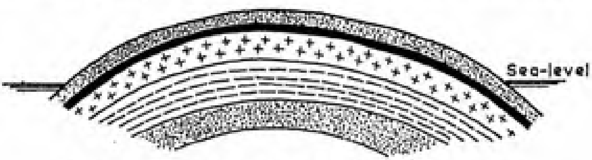


FIG. 9. UPLIFT IN THE FORM OF AN ANTICLINE

the springs would arrange themselves at equal distances apart at the corners of equilateral triangles as shown in Fig. 10. This results in the development of two sets of streams, alternately on each side of the axis flowing into the sea (Fig. 10). These are known as "consequent" streams because their origin is a consequence of the uplift.

Denudation produces a semi-circular depression round the head of each stream and in time these run into each other forming passes

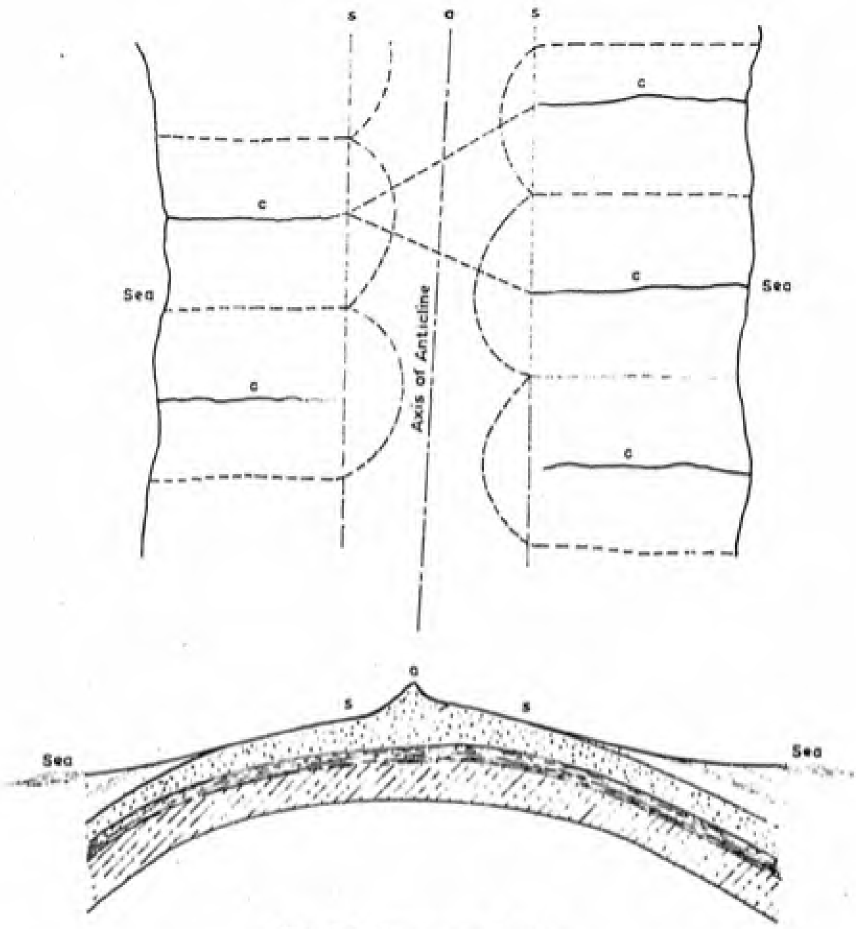


FIG. 10. CONSEQUENT STREAMS

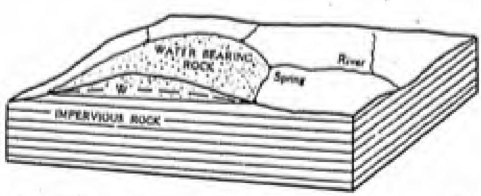


FIG. 11. DIAGRAM ILLUSTRATING THE FORMATION OF SPRINGS

Water falling on the surface of the pervious strata accumulates within it but tends to drain away at its edges where impervious stratum forms the surface of the land. W = the water-table, and springs will be thrown out at the junction of the two rocks, as at "Spring."

or cols (Fig. 12) between the valleys, with high ground standing as a peak at the head of each valley with a ridge running out to divide adjacent valleys. Thus the main watershed shown in Fig. 10 takes on the zig-zag form shown in Fig. 12. Although such an ideal symmetrical system is not realized in nature owing to local variation of conditions, the rivers of Northumberland, Durham and Yorkshire

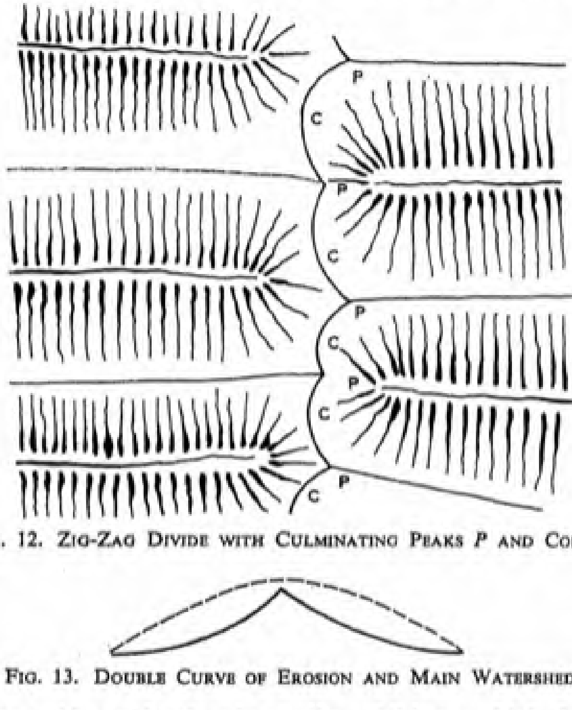


FIG. 12. ZIG-ZAG DIVIDE WITH CULMINATING PEAKS *P* AND COLS *C*

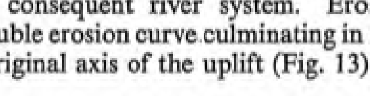


FIG. 13. DOUBLE CURVE OF EROSION AND MAIN WATERSHED

on the East side of the Pennine uplift exhibit to a high degree this regular primary consequent river system. Erosion subsequently will result in a double erosion curve culminating in a high main watershed along the original axis of the uplift (Fig. 13).

Subsequent Streams

The extreme simplification that has been assumed in the immediately preceding description of the inauguration of a drainage system does not obtain in nature, for with variable conditions denudation produces uneven surfaces and subsidiary streams are required for drainage. These are known as tributaries of the main streams and their disposition depends particularly on differences in the hardness

of the rocks. Referring again to Fig. 9, showing an anticline composed of alterations of hard and soft beds, originally horizontal, denudation will result in the hard bands standing up as ridges with

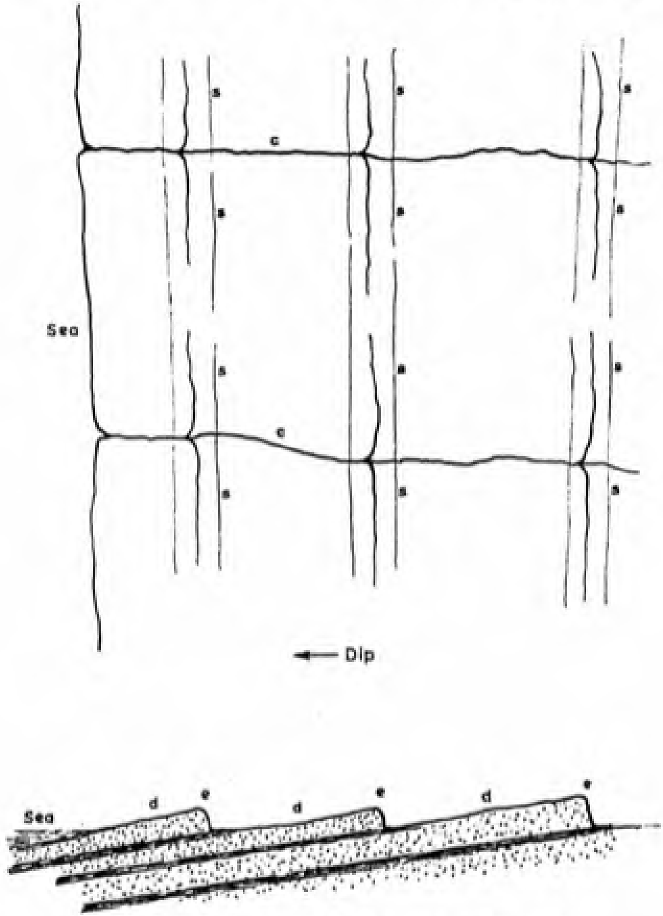


FIG. 14. CONSEQUENT AND SUBSEQUENT STREAMS

Consequents, *c*. Subsequents, *s*.
Dip-slopes, *d*. Escarpments, *e*.

hollows in the softer bands running parallel to the axis of the anticline and at right angles to the direction of flow of the consequent streams. Drainage from the ridges will collect in the hollows and produce streams, known as *subsequent* streams, which will flow along the hollows (Fig. 14). As the general dip of the rocks is towards the

sea in the direction shown by the arrow, these subsequent valleys will be bounded on the seaward side by a steep slope called an *escarpment*, *e* (Fig. 14), and the opposite bank by a more gently inclined dip-slope, *d*. These scarp-slopes may stand up a considerable height and down them may flow, in a direction opposite to the main consequent streams, short, fast-running tributaries to the subsequent streams.

River Capture

The development of a river system and the ultimate area drained by each is by competition among tributaries. The level down to

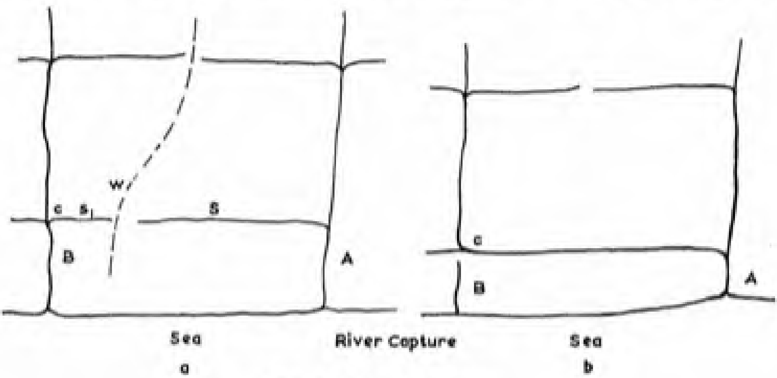


FIG. 15. RIVER CAPTURE

which each tributary can cut is controlled by the level of the main stream at the point of confluence; the grading of the valleys of the tributaries must, therefore, wait upon and be subsequent to the grading of that of the main stream as this is effected back towards the source past the successive points of confluence. The rate of erosion of the different streams and tributaries will vary and be dependent upon ground contour, rainfall and consequent volume and type of rocks through which the valleys cut, so that some will cut deeper valleys and some will cut back more quickly at the head. For these reasons the drainage areas impinge upon each other, and, as valley floors may be at different levels, the head waters of one stream may be captured by another stream. In Fig. 15*a*, the subsequent tributary *S* of the consequent river *A*, is more active than the corresponding tributary S_1, of river *B* and in consequence, the divide between them is driven back to the position *W*, thus enlarging the drainage area tapped by *S* at the expense of S_1. The extra volume of

water acquired by S will further increase its activity relative to S_1, and in time it may be able to cut through the watershed W, between them. If S is at a lower level than the point of confluence, C of S_1, with B, the headwaters of B above C will be diverted down the valley of S into B. This diversion is known as river capture and B is said to have been beheaded by the tributary S of A. The lower part of the valley

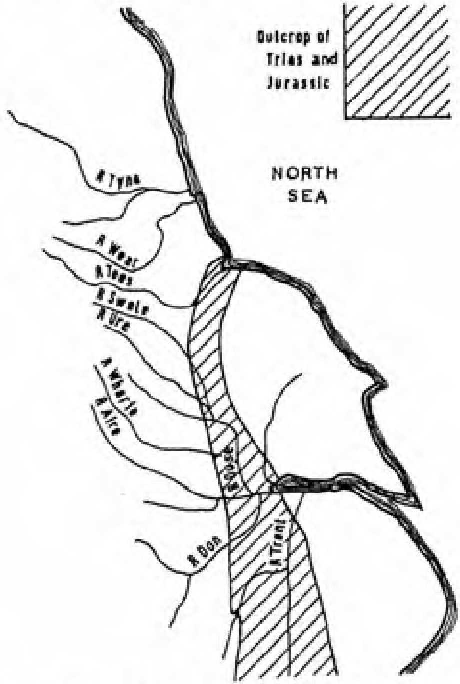


FIG. 16. RIVER CAPTURE BY THE OUSE IN YORKSHIRE

of B is left dry or with only a small *misfit* stream B (Fig. 15*b*), with a pass or *wind-gap* leading from its valley into that of A opposite a sharp bend in the river.

Such river capture may continue progressively as the activity of a particular river is increased with the augmenting of its drainage area and volume by capture. A notable example of such river development is the Ouse in Yorkshire (Fig. 16). The rivers Tyne, Wear, and Tees north of the Ouse and its tributaries, flow down dip slopes from the Pennine Chain as consequent rivers and have been comparatively unaltered in course, except for a measure of rejuvenation or subsequent minor uplifting since the major uplift which

produced the Pennines. The tributaries of the Ouse to the south of them, however, have had a different history. They were formerly also consequent streams, flowing eastwards to the North Sea, which have been successively beheaded by a tributary of the Aire, now known as the Ouse, which flowed along the soft belt of Trias in a southerly direction. This probably explains the development of the present system. The tributaries of the Ouse are still cutting back into the watershed between it and the Tees which has now been reduced to a height of 150 ft.

River Rejuvenation

When a river, before it is graded, passes over a hard rock underlain by softer strata, waterfalls result. A typical case is High Force, 70 ft in height, at Middleton-in-Teesdale where the Tees flows over the Whin Sill, which is much harder than the limestone and shales of the Lower Carboniferous. Above this fall is Cauldron Snout also produced by the river flowing over the Whin Sill. But rapids and waterfalls may also be the result of river rejuvenation produced by uplift of the land in the lower part of the river's course, after this has reached its base level of erosion. The uplift enables the river to recommence downcutting from the mouth upstream and rapids may be caused at the point where the new grade meets the upper portion still at the old grade. If the rate of undercutting keeps pace with the rate of uplift, the river meandering across its flood plain will commence downcutting and a deep meandering valley will be produced across a relatively high plateau. These are known as *incised meanders* and are certain evidence of uplifting. The Wear, between Sunderland and Durham, provides in this way evidence of uplift of the NE. coast and the strategic position of Durham Castle and the Cathedral, enclosed by the bend in the river on three sides, depends on such an incised meander. Where the uplifting takes place in a series of steps or stages, the river will form flood planes at different levels and if the succeeding flood plains are progressively narrower, a series of river terraces of river deposits will be left, as in the case of the Thames.

When sinking of a coastal region occurs, the lower portion of the river valley becomes drowned and the site for the deposit of river sediment and the valley forms an estuary.

Antecedent and Superimposed Drainage

Consequent drainage is evidently the result or consequence of uplifting and is produced by the form or structure of the anticline over one limb of which the rivers flow. But such relation between

the drainage system and the underlying rock structure is not invariably present and where this is the case the drainage system is called *inconsequent*. The two most important examples are the following. Antecedent drainage results where uplifting occurs but the rivers are able to cut through the barrier raised in a portion of their courses and so keep their existing channels open and are not diverted. This is termed *antecedent* since the direction of flow was determined by conditions antecedent to the earth movements which now determine the configuration of the drainage area.

Superimposed drainage occurs where the rocks, whose structure originally determined the direction of flow of the rivers, have been denuded away, so that the rivers now flow over rocks with a different structure into which they have cut valleys following the original directions. The river systems of the English Lake District and of South Wales are of this type.

Lakes

Lakes vary in size from the small tarn or mere to the inland sea, such as the Caspian. The modes of formation of lakes render them divisible into four classes—barrier lakes, rock basins, lakes produced by earth movement and crater lakes.

The first are by far the commonest and all manner of circumstances may interfere with normal land drainage and lead to the production of a lake—a landslip may block the valley of a stream, or a glacier or an ice-sheet may present an ice-wall to the normal course of a river and lead to the filling up of its valley in the form of a lake until it finds an outlet over a pass or col at a higher level and is thus diverted. This frequently happened during the Ice Ages in Britain, in particular to the rivers Esk and Derwent in Yorkshire, but the most fruitful source is deposition of moraine and glacial drift. The English lakes, with one exception, are believed to be barrier lakes of this type, in part at least, though as some descend below sea-level in the deepest parts, it would appear that these portions belong to the second class and are rock-basins, filed out by glacial action and the detritus conveyed uphill, work which could not be performed by river corrasion. During the artificial deepening of Thirlmere to form a reservoir for the city of Manchester, investigation proved that this was purely a rock basin. A number of lakes in Scotland have a similar origin, including the sea-lochs of Etive and Leven. Earth-movement, by cutting off a portion of a sea, has been responsible for the production of some of the largest lakes. The inland Caspian sea has this origin. The craters of extinct or dormant volcanoes are often filled with water forming the so-called crater lakes.

Lakes, unless deep rock basins, do not appear to have long lives, geologically speaking. They become filled with detritus from the streams draining into them, and in tropical climates, evaporation may exceed drainage into them and drying up with the deposition of dissolved magnesium, sodium, potassium and calcium salts, then takes place. Many chemical deposits worked commercially have this origin.

EROSION BY SNOW AND ICE

Snow and ice are powerful geological agents both of corrasion and of transport. They are important in cold climates and at high elevations, above the snow-line, in warmer climes. The height of the snow-line depends on the latitude, being at a height of about 16,000 ft in the tropics, 4,000 ft in Britain and at sea-level in the Arctic and Antarctic.

Snow is mainly important as the raw material of glaciers, but it may have a direct eroding effect when the snow comes into violent motion in the form of avalanches. These are produced when snow falls in winter on an inclined surface in a dry powdery form which does not cohere, the snow slipping off the inclined surface when a sufficient weight has been deposited, or when the snow melts in the spring during a thaw and becomes wet and heavy and again slips off inclined surfaces.

The formation of perpetual snow-fields requires not only a latitude or an elevation at which the mean annual temperature is below freezing-point, but sufficiently humid winds so that the rate of deposition of snow is greater than the amount removed by melting in the warmer season. The snow-line is therefore the level at which there is equilibrium between deposition and subsequent melting. Accumulation above the snow-line may be disposed of by the movement of glaciers. Whereas in dry but very cold regions, such as Siberia, precipitation in winter may be insufficient to overbalance summer melting, in Greenland the snowfall is heavy, accumulation takes place and the depth becomes sufficient to produce pressures which convert the lower layers to ice and forms what is termed a *névé*. Rivers of ice flow from this in the manner of a viscid fluid. The speed of flow is relatively low, in the region of only a foot per day, and the ice base follows the contour of the ground and is therefore uneven. In addition, due to friction between the floor and sides, different layers in a glacier travel at different speeds. For these reasons crevasses or deep transverse or longitudinal cracks are formed (Fig. 17A) which, owing to the greater speed of the middle of the glacier, take a course up-stream as shown in Fig. 17B. As frost riving and mechanical

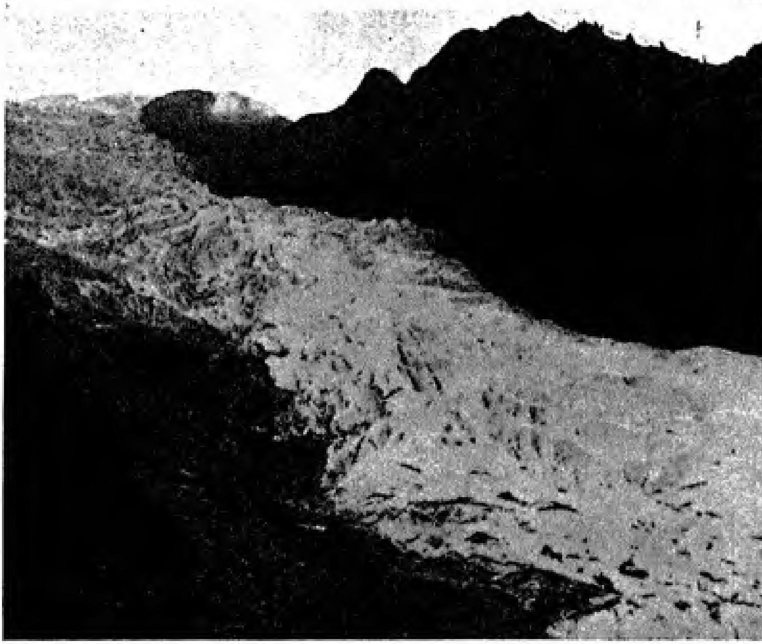


Fig. 17A. Glacier des Bossons, nr. Chamonix, Showing Crevasses and Lateral Moraine

(J. G. C. Anderson)

Fig. 17B. Crevasses, *c*; Terminal Moraine, *m*

weathering of the rocks on the sides of the glacier are taking place, angular rock fragments are transported along with little or no further comminution, on the surface of the glacier, there being a line of angular stones near each side which is called a *lateral moraine*. If two ice streams run together they continue to move side by side without intermingling and the two inner lateral moraines combine to form

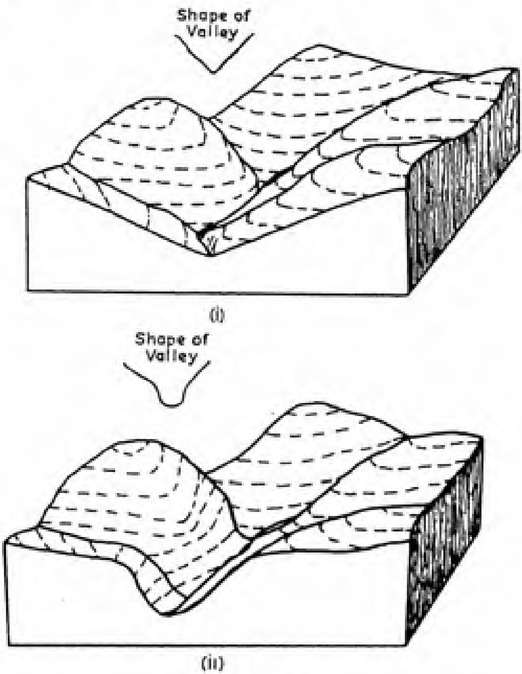


FIG. 18A
(i) River erosion. (ii) Modification by ice.

a *medial moraine*. Although fragments which ride on the surface of a glacier are substantially unaltered, many of them fall down crevasses and are frozen into the sole or bottom ice layer and in this position become a very powerful agent of corrasion, acting like a coarse file on the rocks over which the glacier flows, scratching and striating them and grinding to rock flour both themselves and the particles they dislodge. Such action has caused modification of pre-existing surface topography produced by water erosion during the Great Ice Ages, for there were a number of successive periods with warmer spells between, all over NW. Europe including Britain. The relative

rigidity of moving ice has led to the planing off of spurs and the straightening of former river valleys, the floors of valleys have been gouged out from the V-shape of water erosion to the U of ice erosion, as shown in Fig. 18 with the tributaries left as hanging valleys ungraded to the main valley, and "dry channels" (Fig. 18B).

At the "firn-line" or "bergschrun," where the glacier leaves the parent snow-field, semi-circular depressions, known variously as

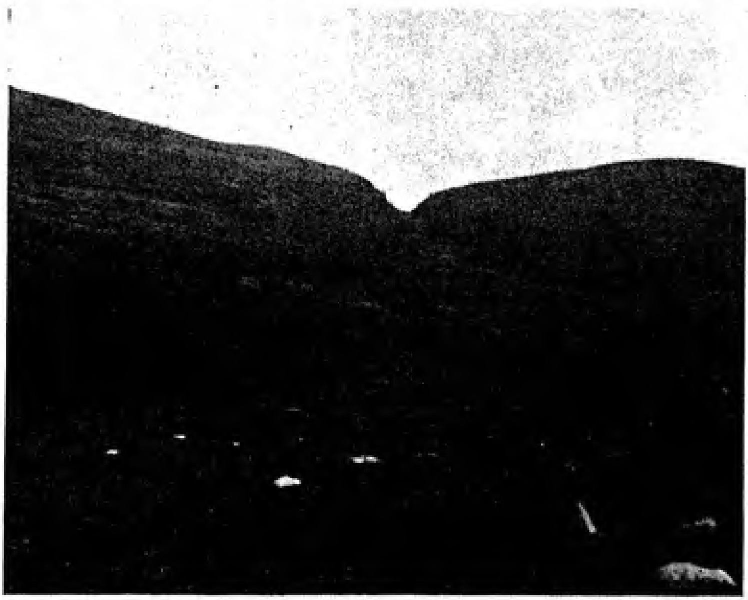


FIG. 18B. DRY CHANNEL, NORTH OF CREAG NA LEACAINN, CAIRNGORM MOUNTAINS
(J. G. C. Anderson)

cirques, cwms or corries at the heads of valleys, are characteristic of glacial action. On the upstream side of rock masses over which the glacier passes scoring and scratching occur and a rounded, polished surface is produced, while on the downstream side a rough, irregular surface, produced by plucking, is formed. These "roches moutonnees" are also a hall-mark of glaciation. "Erratic boulders" and "perched blocks," weighing up to hundreds of tons and carried perhaps many hundreds of miles from their source, left stranded by the melting ice are further signposts. One further indication of previous glaciation is the gouging out of rock basins, now the sites of lakes, and the heaps of unsorted, unsized moraine material, often

crescent shaped, left by retreating glaciers, already referred to in connection with lake formation. Streams of water flow under and through glaciers as sub-glacial and en-glacial streams and these pick up a considerable quantity of rock flour which renders them turbid. From the melting terminal of the glacier streams flow away, also loaded with detritus, which give rise to outwash gravels and silt on the southerly margin of the glaciated region.

Ice Sheets

Where a large area is covered by an ice sheet or ice-cap, as in Greenland, thousands of square miles in extent and several thousands of feet in thickness, the movement of this enormous area and weight of ice although it does not flow in valleys and so have projected upon it moraine material from the rock sides, acts as a gigantic plane over the surface, particularly as the speed of movement is much higher, about 50 ft per day, and the lower levels become so charged as to be practically entirely a mixture of rock flour, rounded, scratched and grooved boulders. This is deposited where the ice-sheet ends, generally as a vertical wall of ice. Such sheets of an unsorted mixture of boulders and clay known as *boulder clay* have been left behind by the ice-sheets which invaded the British Isles from a number of different directions during the Pleistocene or Great Ice Age in very recent geological times which also saw the dawn of man on this planet. Such a heterogeneous mixture could not have been deposited by water, since the velocity of the water necessary to move boulders would never have allowed the clay to settle out. Boulder clay is not without its importance in coal mining. Many of our undersea workings have a thick layer of boulder clay between the eroded surface of the Coal Measures in which the seams occur and the sea, and this forms a flexible waterproof sheet of great utility in preventing inrushes of water from the sea-bed into the workings in the shallow seams. Its absence would necessitate the leaving of a much greater depth of "cover" between the workings and the sea-bed which would sterilize large areas in the shallow seams.

Although the Pleistocene Ice Ages are of great interest and importance in connection with the geology of NW. Europe, Ice Ages have recurred sporadically throughout geological time from and including the Pre-Cambrian, probably some 2,000 million years ago. Evidence of former Ice-Ages exist in what are now tropical countries, for example, that of late Carboniferous Age (contemporaneous with the Coal Measure forests of the British Isles) in South Africa, Australia, India and South America. Explanations of the causes of Ice Ages are still in the realm of geological speculation.

MARINE DENUDATION

The agents of marine denudation are waves, produced by wind, currents and tidal action. Currents are due to a complex interaction of tides, winds and variation of marine temperature, the tides to the rotation of the earth and the variable gravimetrical attraction of the sun and the moon. Wave action armed with the products of denudation is the most potent agent in the actual breakdown of the rocks. Tides and currents, aided by wave action, affect transport and removal of denuded material, and also influence the subsequent re-deposition of the material.

As would be expected, the actual pressure exerted by waves upon the rocks on which they impinge varies with the season of the year and reaches a high maximum value in winter storms, as their destructive action on man-made esplanades and coast defences bears witness. In summer Atlantic rollers exert a pressure of about 600 lb/ft^2 and in winter 2,000 lb/ft^2, while pressures up to 3 ton/ft^2 have been recorded in storms. Wave action operates between the level of the wave trough and its crest, but the actual effects may extend to an indefinite height above this, first by the undermining effect of the waves, particularly in a soft band overlain by a harder layer, which ultimately brings into play the effect of gravity on the beds above in the production of a cliff fall, and secondly, by compressing air trapped in joints and fissures in the rock. This exerts a wedging action which widens the cracks, and imparts a sharp, shattering blow to the material on the sides. The material picked up by the waves, rock fragments produced by sub-aerial denudation and by bombardment from other fragments of like origin, is rolled about by the swirl of the waves and is gradually reduced in size and rounded. In storms large boulders are lifted and hurled about but the buoyancy effect of water in reducing the specific gravity of the material from, say, an actual 2·6 to an effective 1·6 when immersed, should not be forgotten. Where the waves break on hard rocks a platform, gently sloping seawards, is often produced (Fig. 19). Between the low- and high-tide marks, this platform may be bare of material if the rocks attacked are hard and the rate of erosion slow. In softer rocks, a beach with shingle and sand may result owing to the greater depth of the platform cut in the softer rock upon which material can remain and accumulate to form a beach. There is a tendency on gently sloping shores for material above a certain

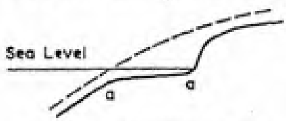


FIG. 19. FORMATION OF WAVE PLATFORM a–a

critical size to move landwards while the smaller material moves seawards. The reason for this is that wave action takes the form of a quick forward motion of the water followed by a much slower backwash. Both large and small particles are lifted on the forward stroke but the gentle backwash can only suck back the smaller material. The result, therefore, is an accumulation of large pebbles or cobbles near the high-water mark (Fig. 20), and then the material becomes progressively smaller seawards until, outside the limits of

FIG. 20. A BEACH OF LIMESTONE PEBBLES AT BARRY, GLAMORGAN

The pebbles have been produced by the action of the waves upon fragments of rock derived from the distant cliffs; the beach illustrates the tendency for the separation of the fine sand and mud from the pebbles.

wave action, the finest material only is deposited in deep water (Fig. 21A).

Owing to prevailing winds, waves generally travel shorewards at an oblique angle to the sloping shore and the material carried by the waves is thrown on the shore in the same oblique direction. The more gentle backwash, however, sucks the material back along the steepest gradient, so that the actual path of a particular pebble as it is thrown forward and sucked back by the waves is a series of zigzags, forward obliquely and straight back.

The resulting movement of material along the shore is known as alongshore drift and results in the production of banks of shingle from eastward migration of material on the South Coast bordering the English Channel and southwards on the East Coast in accord with the direction of the prevailing wind and without the assistance of tides or currents. Well-known banks of shingle produced in this

manner are the Chesil Beach near Weymouth, Spurn Point at the mouth of the Humber and that at the mouth of the Alde near Orford Ness in Suffolk. The banks are often sited near the mouths and estuaries of rivers owing to the action of the outflowing river current.

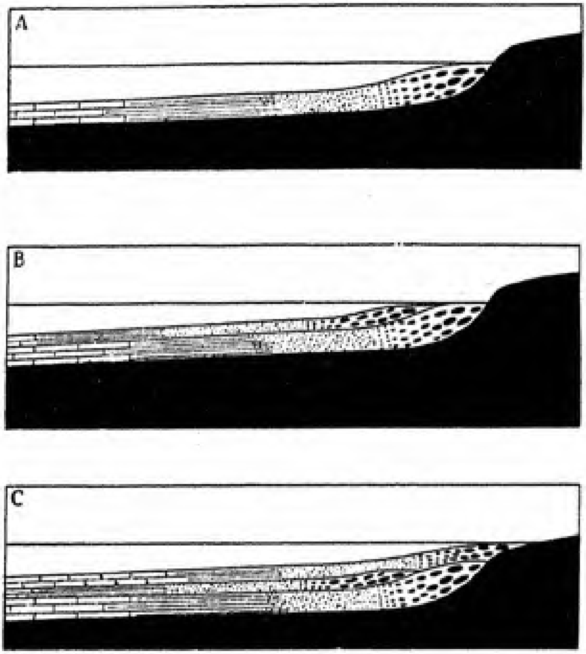


Fig. 21

(A) Stratification with stationary or rising coast-line. (B) Stratification with sinking coast-line. (C) Successive sea-levels.

Types of Coast Contour

Broadly two main types of coast line may be distinguished, namely coasts of *submergence* and coasts of *emergence*. The former are produced when either active coast erosion is taking place or the land in the vicinity is descending, probably by earth movement but in any case its level relative to sea-level is being reduced over a wide area. The latter presents both phases of the converse case. Either new deposits are being built up which carry the coast line seawards or the land is rising. Both forms are present in these Islands. As a complete whole the land surface generally is, of course, being reduced in level by the various agents of denudation, but without regard to the relative agricultural value of gains and losses,

a Royal Commission which investigated the position in 1911 reported that the increase of area of these Islands in the past thirty-five years exceeded the losses in the ratio of over 7 to 1, 48,000 acres against 6,600 acres. Generally speaking the West Coast is being augmented, as the difficulty of keeping open the channel to the port of Liverpool well illustrates, while the East Coast is retreating as the loss of important sea-ports within historical times bears witness. Emergence in past ages is shown by raised beaches and river rejuvenation, and is characterized by simple, straight coast lines of similar, relatively unconsolidated rock with little or no indentation or relief. Deltas are also a common feature of an emerging coast line. Submergence on the other hand with the drowning of valleys, particularly if these are young with sharp V valleys, produces sharply-indented coast lines with estuaries reaching far inland. Forests now drowned below the sea level are further evidence of submergence.

Cliffs

The rate of marine erosion depends upon a number of factors and in particular upon the resistance of rocks, including their inclination, hardness, presence of joints, bedding-planes and other fissures, the frequency of storms and the strength and direction of the prevailing wind. If marine erosion is more active than sub-aerial denudation, cliffs result but this does not of necessity imply hard rocks. Some of the highest cliffs occur in relatively soft strata such as Chalk, Lias and Boulder Clay, but harder rocks with well-marked jointing will also form cliffs and off-shore stacks (Fig. 22) particularly if they are inclined (dip) towards the sea. When rocks of different hardness are exposed along a coast, the softer parts at first are eaten back forming curving bays and coves with the hard rocks standing out as headlands which are then subjected to the brunt of marine attack both frontal and on the flanks so that the average rate of erosion of the coast line is reduced but takes place evenly in the hard and soft rocks alike.

With a gently-sloping shore, waves may break a fair distance out from the coast with the formation of a sand and shingle bank with a lagoon of deeper water between this and the fore-shore.

Wind Erosion

The present moist climate of the British Isles is not conducive to wind acting as an important agent of denudation except in the formation and migration of sand dunes in coastal areas, rendering the planting of marram grass necessary to maintain them in place and prevent the deterioration of valuable agricultural land. In past

ages, however, and notably in the Old Red Sandstone and New Red Sandstone periods, desert and semi-arid climatic conditions obtained with inland seas which were drying up, similar to the Dead Sea and

Fig. 22. Off-Shore Stack, Middle Old Red Sandstone, Nr. Gaulton Castle, Orkney
(J. G. C. Anderson)

the Caspian of the present day. In true deserts, except for an occasional cloud-burst, there is practically no rain and weathering takes place through temperature scaling as there is a high diurnal temperature range, and chemical action by strong solutions drawn up from below by capillarity. Chemical weathering may extend deeply and disintegration gives a plentiful supply of fine material for transport by the agency of wind, the sole means of removal. Wind, like ice,

can transport material uphill and also acts as a sorting agent so that aeolian deposits show stratification or arrangement in distinct layers, but these, like some quickly laid-down water deposits, show "current" or "false" bedding, that is, the different layers are not parallel to the top and bottom of the bed considered as a unit. The buoyancy and viscosity effect of water is absent so that the full weight of the particles borne by the winds is available for erosive sand-blasting action on exposed rock surfaces, imparting a characteristic patina or burnish. At the same time, the particles themselves are comminuted and are exceptionally well rounded even down to sizes $\frac{1}{100}$ in. in diameter, as evidenced in the "Millet" Seed Sandstone" of Lancashire and Cheshire, which if carried by water, would escape rounding because of buoyancy. The fineness of the grains enables them to be transported by wind for great distances and in this manner dust from the Sahara is carried by the mistral to Italy and the South of France. The "loess" deposits of the prairie and steppe lands of North America and Russia consist of such air-borne dusts from deserts and from the rock flour of glaciers mixed with humus, and are extraordinarily fertile. An example is the Black Earth of the Ukraine.

In the deserts themselves the position of the sand-dunes is the result of complex local air currents and the sites of many of them are permanent, though change of local conditions may cause down-wind migration. Dunes have a gentle slope on the windward side and a steeper slope on the leeward side caused by plucking by wind eddies. The migration of sands and dusts is of interest to mining engineers in connection with the suppression of coal-dust explosions as the same laws govern the "dispersibility" of coal and stone dusts, that is, the ease with which they may be raised in a cloud.

QUESTIONS

1. Describe the effects of weathering in a temperate, humid climate.
2. Write a short essay on river development and the different types of river drainage. What do you understand by river capture?
3. Describe the work of (*a*) Wind, (*b*) Ice, as geological agents.
4. Give an account of the formation of cliffs.
5. How and in what circumstances are the following geological structures formed—

River Terrace,
Alluvial Deposit,
Continental Shelf,
Geosyncline?

CHAPTER IV

THE SEDIMENTARY ROCKS

SEDIMENTATION

It has already been remarked that in the region of the storm line deposits left by marine erosion, flung up by storms, consist of cobbles with smaller pebbles between; then, seawards, the deposits progressively show downward gradation in size of particle until finally only fine mud is deposited on the edge of the continental shelf and the slope leading to the oceanic deeps. Mingled with these inorganic deposits are whole and broken shells and other remains of fishes. From the shore outwards therefore, although there is no hard-and-fast division between them, marine deposits may be postulated as a succession of belts arranged parallel to the shore line, each belt consisting of material of similar composition and of the same order of grain size. These belts are arranged in the following order—from the storm-line to low-water line—cobbles and boulders grading into gravels, sands and shell banks; from the low-water line to a depth of approximately 600 ft; sands, silts, and calcareous deposits. (This belt is sometimes known as the Belt of Variables since although the materials may show good sorting and grading, this is in patches, rather than in zones.) In the deeper waters below 600 ft is the Mud Belt and beyond this on the ocean floor, outside the reach of land-derived sediment, are oozes and Red Clay, the latter derived from volcanic and meteoric dusts which settle from the atmosphere.

The indefinite belts outlined above vary widely in width. Thus the storm beach may be only a few yards wide, while the mud belt spreads over a wide area to the edge of the continental shelf. Deposition in the vicinity of estuaries and river mouths is somewhat different and the mud belt may encroach on the sand and gravels. This has been explained as follows. It is suggested that each particle of fine mud or clay carries a slight electrical charge which, when the river meets sea-water at the mouth, is neutralized since sea-water acts as an electrolyte, and the particles are now able to clot together and be deposited with the sand. This flocculation explains the mud-flats and estuaries at river mouths in contrast to the much cleaner sorting and grading in lakes where, in the absence of an electrolyte, the mud particles retain their individuality.

Grain Size of Sediments

Although an international classification by grain size of sediments and the rocks resulting from them has not been entirely accepted the following seem to be the most favoured—boulders exceed 8 in. in diameter; cobbles are between 4 and 8 in. in diameter; gravels lie between 4 in. and 2 mm; sands between 2 mm and 0·05 mm; silts (intermediate sediments between sands and muds) from 0·05 mm to 0·005 mm; and muds and clay minerals are less than 0·005 mm in diameter. Muds are of various colours, blue being the commonest, the colour being due to carbon or to iron pyrites. Red mud is coloured by ferric oxide or hydroxide resulting from tropical weathering. Green mud owes its colour to the presence of glauconite, a hydrated silicate of iron and potassium. Sometimes in the case of a large river with tributaries draining a very wide area, these tributaries come into flood successively in different periods of the year and may bring down different materials forming muds of different colours. Muds, when first deposited, contain 80 to 90 per cent of water. When these are buried, water is squeezed out and a plastic clay results still containing 30 to 35 per cent of water. Still deeper burial leads to the expulsion of this water and the formation of a mudstone or bind, or, if laminated, that is arranged in a series of very thin layers one above the other, a shale.

In addition to the inorganic sediments, as already mentioned, shells, broken and unbroken, are deposited and these frequently occur as beaches and shell-banks as on the West Coasts of the British Isles and in Holland. Coral mud occurs in the neighbourhood of coral islands and calcareous oozes, such as Globigerina ooze, reach the fairly deep parts of oceans down to 15,000 ft but are dissolved before reaching the greatest depths where only siliceous oozes, such as Radiolarian and Diatom ooze, are to be found, together with the Red Clay.

Stratification and Lamination

It will have been remarked by those with any experience of coal mining that a given bed or group of beds of a sedimentary rock is not constant over wide areas but tends to change from a sandstone to a stone-bind and then to a shale or bind. In like manner it will be realized that a similar gradation will occur in the sediments deposited on a sloping shore as shown in Fig. 21A, greater thickness of coarser material is being deposited near the coast, and if no earth movement is proceeding, accumulation near the coast may cause a shift of the different zones seawards so that coarser material is deposited on

finer material. The same result will take place if the coast is rising. If, on the other hand, the coast is sinking, then the finer material will overlap the coarser as the zones shift landwards (Fig. 21B). The thickness and the type of sediment deposited at a given site will therefore depend on the type of material available, the depth of the water and the effect of waves and currents. As these change, so a

FIG. 23. STRATIFICATION AND JOINTING IN CLIFFS AT LAVERNOCK, NEAR PENARTH

The bedding planes and joints constitute planes of weakness, on account of which, the rocks (limestone and shale of Lower Lias age) are subject to frequent falls; the fallen material is broken up and removed by the waves. (F. F. Miskin)

change will occur in the sediment and this results in the layering or bedding of the deposits, each layer slightly different from that above and below it. This is known as *stratification* (Fig. 23).

In muds which are deposited in thin layers over wide areas, each layer may represent material deposited by a flood, a pause in deposition occurring until the next flood period. If the mud is deposited in an estuary between high and low tide marks, each layer is slightly hardened by exposure to sun and wind before the next is deposited. In addition to these time or pause-in-deposition effects, flattened particles, and in particular flakes of mica, are deposited with their longer axes horizontal. These effects result in material being deposited in very thin individual sheets and when hardened they may be split horizontally into layers sometimes as thin as $\frac{1}{100}$ in.

The material, of which a shale is the commonest example, is then said to be *laminated*. There is no hard-and-fast division between stratification or "bedding" and lamination. The distinction is one of degree only. In the former the division or bedding planes which mark the bottom and top of each layer are relatively far apart: they may be several feet in a "freestone," a sandstone of homogeneous

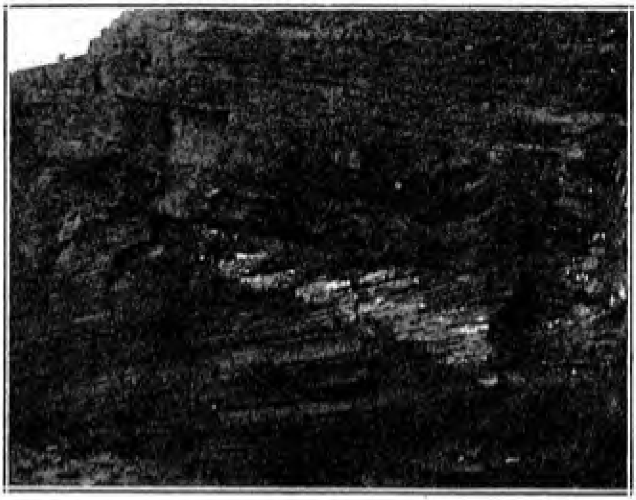


FIG. 24. FALSE-BEDDING OR CURRENT-BEDDING INDICATIVE OF SHALLOW WATER ORIGIN, IN THE SO-CALLED "MILLSTONE GRIT," NEAR LLANGOLLEN
(F. F. Miskin)

texture used for building, and only a small fraction of an inch apart in a well-laminated shale.

False or Current Bedding

The sediments previously described have been assumed to have been deposited in horizontal sheets. Actually, owing to the shelving shore-line they will be slightly inclined seawards and will be of a very elongated lenticular-shape owing to the higher rate of deposit landwards.

Sometimes, and particularly in sandstones, although the top and bottom bedding planes are parallel in a layer of material, intermediate planes may run at different and high angles to the boundary planes. This is known as false or current bedding (Fig. 24). It probably results from the rapid deposition of sand and pebbles in heaps in deltas or elsewhere where currents change direction through

local causes and the material carried is dropped in a number of adjacent heaps with axes at various angles to each other. Wind-borne deposits also exhibit current-bedding, as already mentioned.

Fresh-Water Deposits—Lakes

Where a river meets the sea at the mouth of an estuary its velocity is checked and it begins to deposit its load. Similarly where it runs in at the head of a lake its carrying power is reduced in the same manner. Better grading and sorting takes place in a fresh-water lake than in the hydrolized water of an estuary, and material is deposited in order of coarseness. A delta forms and will ultimately result in the filling up of the lake. At first a sand-bar is formed (Fig. 25) and the stream divides into two. Further bars are formed, *B*, *C*, *D* and *E*, and the river further subdivides. Finally a large triangular-shaped alluvial flat is formed with finer material at the base, deposited in the less-rainy seasons, on which coarse material is thrown down in heaps in times of flood. Flood water may then remove a portion of the material already deposited and substitute in the channel so scoured out fresh material of a different kind. This is one method by which a wash-out occurred in the deltaic deposits known as the Coal Measures. Streams running into the lake at the side also form deltas which extend across the lake and in time may divide it into two parts. This has happened in a number of cases in the English Lake District. Thus, Derwent Water and Bassenthwaite once formed a single lake some nine miles in length as, also, did Buttermere and Crummock Water.

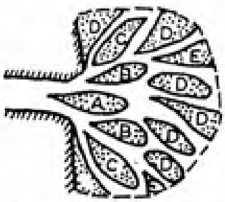


FIG. 25. FORMATION OF A DELTA
A, B, C, D and *E* Sand-bars.

Deltas in lakes, though important geologically as the means by which the relatively short life of a lake is terminated, are much less in size and importance than the deltas at the mouths of large rivers, though the mode of formation and configuration are similar. To the coal-mining engineer, as already suggested, deltas and deltaic deposits are of first-rate importance, for the bulk of the coal seams were laid down in such conditions and many of their vagaries and those of the rocks associated with them are understandable if the conditions of deposit are realized.

Residual Deposits

These consist of the products of weathering which have remained *in situ* and have not been transported by water, wind or gravity. In

some cases these are the insoluble constituents, such as the sand grains of a sandstone with a calcareous cement which has been dissolved away. Clay-with-flint cappings, bauxite (the main source of commercial aluminium), laterite (a red or brown clay which is soft when freshly excavated but hardens on exposure to air), Kaolin or china clay are all residual deposits; but the commonest and most important is soil. This is a mixture of rock waste and mineral waste with humus, which is the decaying remains of plants and animals peopled by myriads of bacteria. The character of the soil is largely dependent upon the type of rock from which the soil is derived, but climate has an effect and in the tropics this factor takes control.

Soils, or seat earths below coal seams give information of the conditions under which coal-measure plants grew and this aids in the elucidation of the mode of coal formation. Peat, as the intermediate stage of coal formation, is also of importance and will be discussed in greater detail in later chapters.

Petroleum, also classed as a residual organic deposit, does not retain traces of its former components as does coal and peat, and in most cases has migrated from its place of formation and is now discovered floating on water, often saline, under the arches of anticlines and beneath an impervious capping which has prevented further migration and loss.

The alluvial deposits which occupy the flood plains of rivers are also an important source of mineral ores through the sorting of deposits which results in the concentration of the highly disseminated traces in many rocks. These placer deposits, as they are known, are exploited for gold, cassiterite (tin oxide), monazite (for thorium and cerium), platinum and diamonds.

As an increasing thickness of sediment is deposited, pressure is increased on the lower layers, the grains become packed more closely together and water is expelled from between them. The combination of increased pressure and loss of water results in the formation of clays, mudstones, or binds, and shales, and is accompanied by some chemical change and recrystallization brought about by increase of temperature with increased depth of burial.

In a porous rock, such as a sandstone, the process of hardening or compaction from the original sand from which the sandstone is derived, is accompanied by the cementing of the grains by silica, calcium carbonate or iron oxides and both the colour and the strength of the resulting sandstone is largely determined by the character of the cementing material which is leached out from other sources and redeposited from solution as the water percolates between the grains. During the process of drying out and compaction

the layers in which the rock is deposited are emphasized and the bedding planes are accentuated. The shrinkage also produces vertical joints or cracks which although "closed" when buried at depth, tend to open when denudation removes superincumbent material, allowing carbonated water to enter and accelerate the weathering and break-up of the material.

Rudaceous or Pebbly Rocks

The limits of grain size of the particles constituting the various types of sedimentary rocks, have already been enumerated. It should, however, be realized that the limits of size are closer in the smaller-grained rocks. The interstices between the large cobbles and pebbles of the rudaceous rocks are occupied by material of smaller grain size, such as sands and smaller pebbles, as they are on an ordinary storm beach.

Where the pebbles are well rounded, as is usual with marine deposits but less emphasized in river gravels, the rock which results from consolidation is known as a *conglomerate* (Fig. 26). Those from terrestrial deposits, such as screes with irregular and angular shaped stones, when compacted are known as *breccias*. The type of rock of which the pebbles are composed, many of which would appear to have travelled long distances from the rocks from which they were derived, is of importance in reconstructing the physical geography of past geological eras.

It is important to realize that sedimentary rock constituents may be used again and again in successive geological systems, erosion being followed by re-deposition and erosion again, and that when once rounded by water erosion, fresh-water or marine, the particles may be re-incorporated in different geological formations with little change of shape.

Arenaceous or Sandy Rocks

Of these, quartz is generally the most important constituent and the character, strength and colour of the sandstone is influenced particularly by the type of cement compacting or binding together the grains. This cement may be siliceous, calciferous or ferruginous.

The coarser sandstones are known as *grits*, and break with a rough surface which also shows small pebbles. They are hard, have a siliceous cement and are used for millstones. The well-known Millstone Grit or Farewell Rock immediately below the Lower Coal Measures is a typical grit and weathers into large blocks. This is a typical deltaic deposit.

The white and light grey sandstones also generally have a siliceous

cement and when this occurs as a secondary growth in optical continuity with the crystal from which the quartz grain was broken, the rock is known as *quartzite*. Other quartzites are produced by thermal metamorphism from sandstones, the quartz crystals then

FIG. 26. CONGLOMERATE, NEAR ROVA HEAD, SHETLAND
(J. G. C. Anderson)

being reconstituted by heat and recrystallized. In some light-coloured sandstones the cement is calcium carbonate, and when this takes the form of calcite the rock is known as a calcareous sandstone.

Yellow and brown sandstones have a cement of hydrated ferric-oxide, while red sandstones are generally wind-worn grains deposited as sand-dunes under arid and semi-arid climatic conditions with a cement of ferric-oxide. When the sandstone breaks into slabs parallel to the bedding planes, the rock is known as a *flag* and is used for wall cappings and paving. The ease of splitting along these planes is due

to the presence of white mica flakes arranged parallel to the bedding planes.

When quartz is not the predominating mineral the rocks which result are known by local names. If felspar predominates, as the result of the weathering of igneous or metamorphic rocks, the rock produced by the hardening of the sediment by the presence of a siliceous cement is known as arkose. Where the cementing material is deficient or absent, beds of loose sand may be found but generally sufficient material has percolated in by water to produce at least a weak sandstone.

The transition rocks between sandstones and mudstones, or argillaceous rocks, are the silt-rocks, or micro-sandstones, and flags with properties intermediate between arenaceous and argillaceous rocks, into which they often graduate laterally in opposite directions.

They do not, like muds and clays, possess the property of plasticity. They are important to coal-mining engineers as much Coal Measure strata consist of silt rocks, notably the "stone binds."

Argillaceous Rocks

It has already been remarked that compaction of these rocks is not by infiltration of cementing material but by hardening owing to the elimination of water through increase of pressure. Much of the material is in the "jelly" or colloidal state. The composition of muds is as yet indeterminate as the material has been broken down into a very complicated mixture with properties akin to mica and known by the generic name of "clay-minerals." Carbonaceous material and ferrous sulphide determine the blue-grey colour of the commonest muds and the resulting rocks, which again are of great importance in coal-mining. The black carbonaceous "binds" and "batts" are generally weak in strength. The mudstones or "binds" do not show lamination, but the shales or "clifts" do, probably through a high mica content emphasizing bedding planes and pauses in deposition allowing differential hardening and slight differences in constitution. Secondary mica is also produced by chemical action during hardening and this facilitates splitting between layers. When shales are metamorphosed slates are produced with cleavage imposed by pressure often at a high angle to the original bedding.

Clays become plastic through partial drying by superincumbent weight and cracking in irregular directions is common. The "seat earths" of coal seams, known as "seggars" and "clunches," are often impure fire clays which graduate into sandy "stone-clunches." Occasionally pure fireclay or a ganister, with a silica content of over

90 per cent, forms the seat earth. The coal seam and the floor may then be worked simultaneously, refractory bricks being manufactured from the latter. All argillaceous rocks, clays, shales, and mudstones are raw materials of the brick-making industry.

Calcareous Rocks

The main constituent of these rocks is calcium carbonate, generally of organic origin but sometimes produced chemically.

The shell-bands of whole and broken shells when consolidated by calcareous mud or calcite, crystallized out from percolating water, form shelly limestones. Occasionally a ferruginous cement is present and the resulting limestone has a yellow or brown colour. Of the two crystalline forms in which calcium carbonate occurs, aragonite and calcite, the former is unstable and is often recrystallized as calcite. In Carboniferous times, Crinoids or "sea-lilies" produced a great thickness of mountain limestone, particularly in Derbyshire. Similar deposition is taking place at the present time, but at a very much reduced rate, at the bottom of the Irish sea. Coral limestones consist of the skeletons of reef-building corals. Such corals are active in tropical seas of the present day where the temperature exceeds 68°F. Wenlock limestone is of this type. Chalk, similarly, consists of the remains of foraminifera cemented by calcareous mud. It is white or light yellow in colour and, as impurities are low, is practically entirely calcium carbonate. It is porous and therefore waterbearing when deposited on top of an impervious clay. It often contains nodules of silica, known as flints, with sponge spicules. These nodules occur in bands or seams and were worked by the first miners, those of the Middle Stone Age, before farming commenced—thus representing the first skilled craft after that of hunting.

A transition rock between mud rocks and calcareous rocks is represented by the *marls* or limey clays. They were often laid down in fresh-water lakes. The Chalk Marl and some of the Liassic marls contain nearly the right proportions of limestone and silicate of alumina to form cement when burned in a furnace.

Dolomite is a mixture of magnesium and calcium carbonates, the proportions of which vary up to 44 per cent $MgCO_3$, corresponding to the double carbonate, $CaMg(CO_3)_2$. It appears that the majority of dolomites, or so-called magnesian limestones, are sedimentary limestones deposited in inland seas like the Caspian which became more and more saline as they dried up. The magnesium carbonate replaced some of the aragonite and calcite as a secondary enrichment and similar dolomitization has occurred along fault planes and major joints where Carboniferous Limestone

is overlain by new strata of Triassic age. From these percolation of magnesium salts occurs and replacement of some calcium carbonate by magnesium carbonate takes place. In the deeper portions of coral reefs dolomitization occurs through percolation of magnesium salts from the overlying sea-water.

Much of the dolomite of the NE. coast is concretionary, formed round a fossil as a nucleus, and taking on a number of strange shapes with spherical or "Cannon Ball" structure as the most common type. Anhydrite deposits also occur in magnesian limestones for example near Middlesbrough on the NE. coast. The next geological system

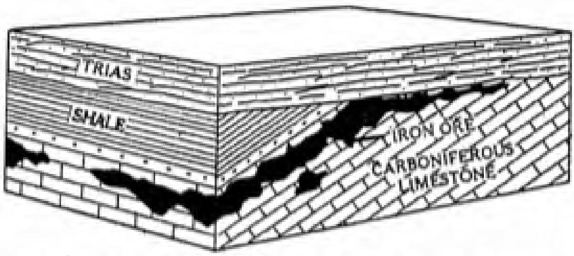


FIG. 27. OCCURRENCE OF HAEMATITE IRON ORE IN LIMESTONE

Showing the conditions in which iron ores occur in association with the Carboniferous Limestone at Llanharry in Glamorgan and in other parts of the country. The ore masses resemble, in shape and distribution, the solution cavities and caverns often seen in limestone.

above the Permian, considered as part of the Trias, also has a characteristic series of limestones known as oolites from the small spherical grains, like the roe of a fish. When the grains are of larger size, about ⅜ in. in diameter, the rock is known as a pea-grit or pisolite. In both cases the grains consist of concentric layers of calcite, exhibiting also a radial structure with a nucleus of fossil shell fragment, sand grain or mud clot. The mode of formation appears to be crystallization of calcite or aragonite from a saturated solution of calcium carbonate round the nuclei, but in some cases calcareous algae may play a part. The Oolitic Limestones are renowned as building stones and include the Portland Stone.

Ironstones

Another replacement product of limestone by solutions descending from the Trias above are the haematite iron ores of Cumberland, North Lancashire and S. Wales (Fig. 27). This ore is ferric oxide, $Fe_2 O_3$, and occurs as kidney-shaped concretions, the masses of ore being formed in very irregular shapes bearing relation to faults which occurred in Post-Triassic times.

The most important iron-ores of this country are, however, sedimentary deposits and are divided into two groups (*a*), the Clay and Black-band Ironstones of the Coal Measures, upon which the iron-smelting practice of this country was developed but which are now of much less importance and (*b*), the Jurassic Ironstones showing oolitic structure analogous to that of the limestones of the same system. In addition there are magnetic ores associated with metamorphism, notably in Sweden and Eastern United States, but these, containing up to 60 per cent iron, are not important in this country.

(*a*) The Clay and Black-band Ironstones are concretionary in form and composed of ferrous carbonate or siderite. The concretions or nodules often have a well-preserved plant fossil as a nucleus and are deposited in the fresh-water shales of the Coal Measures and Wealden (Chalk) ages. In the stagnant waters of the Coal Measure deltas, with a plentiful supply of rotting vegetation giving reducing conditions through bacterial action, hydrated oxides of iron were deposited from solution and converted to siderite, $FeCO_3$. Bog iron-ore is being formed by a similar reaction at the present time.

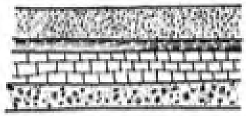
(*b*) The Jurassic Iron-ore deposits of Lincolnshire and of Cleveland in Yorkshire are worked by open-cast workings in the former case, where the dip is low, and by underground workings in the latter case where the strata above the deposit is strong enough to form a reliable roof. The ore consists of small spherical concretions or ooliths formed by chemical precipitation round nuclei and consists of green iron silicate (chamosite), mixed with a high proportion of iron carbonate (siderite). At surface this oxidizes to hydrated Fe_2O_3 with a characteristic rusty-brown colour. The deposit was laid down *in situ* in shallow sea-shore or lagoon conditions with gentle wave action sufficient to roll the particles during accretion and allow of concentric growth.

SUBSEQUENT MOVEMENT OF SEDIMENTARY ROCKS—FOLDING AND FAULTING

The sedimentary rocks were deposited in what are for practical purposes horizontal sheets. Since most shore-lines slope gently seawards there is actually a slight inclination or dip in that direction and as the rate of deposition is greater towards the land, the individual sheets are very elongated lenticles. As long as the sediments are laid down one upon the other, each layer parallel to those above and below, the series is known as *conformable* (Fig. 28), and in the case of deposition in a geosyncline, up to 50,000 ft of strata may be laid down in this manner. There may have been temporary pauses in deposition during the period which must ensue for deposition of this

magnitude, through failure of the supply of material to rivers, deflection of currents on change of climatic conditions or whatever other agent of denudation was operative. Later, the supply may be resumed. Such a gap is known as a *non-sequence* and may be recognized by the absence of fossils, present in other areas where deposition has been continuous.

Ultimately the sinking which has permitted the accumulation of sediments may be arrested and be followed by elevation. This



Conformable Strata

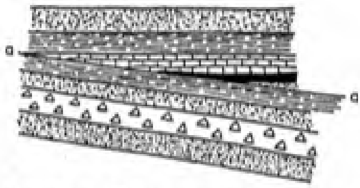


FIG. 28. CONFORMABLE AND UNCONFORMABLE STRATA, SHOWING OVERLAP
a—a Plane of Unconformity.

elevation may take one of two forms, a slow elevation through gentle warping of the earth's crust, with little disturbance of strata, or more violent uplift accompanied by bending or rucking-up of strata, fracturing known as faulting, and a greater or lesser disturbance of the deposits from their original horizontal arrangement, although the parallel arrangement of the different beds will continue. After elevation, erosion again acts upon the uplifted, tilted, or folded strata and in time the irregularities will be planed off and the region will tend in configuration towards the peneplain. If the area now again sinks it will once more become a region of deposition and a new series of sediments will be laid down upon the eroded surface of the older strata. Thus there will be both a prolonged gap in time between the deposition of the two series of sediments and, if the older formation has been tilted or folded the bedding planes of the older and younger formations will be inclined at different angles to the horizontal and not parallel. The junction of the two formations is known as a plane or surface of unconformity (Fig. 28) and the two formations are said to be unconformable. Whatever folding, tilting or fracturing

affected the older formation before the new formation was deposited will, of course, not affect the newer formation, but any subsequent deformation will affect both. As, however, the lines, axes or planes of weakness in the older formation (along which previous movement and deformation took place) remain, subsequent movement is probable along the same axes and will affect both older and newer formations. In the younger formation, however, the total amount of movement or dislocation is less than in the older formation beneath, as the latter exhibits the aggregate of the two movements while the former has been subjected to the later stage only. This phenomenon is commonly encountered in the Permian and Triassic systems above the Coal Measures. The extent of the gap in time and of the strata succession omitted during the period indicated by the unconformity may be determined by reference to areas in which the break in deposition did not occur. The correlation of the top bed of the older and the bottom bed of the new formation with the succession in the region in which deposition was continuous is by fossils, plants or animals, whose remains have been buried and preserved in the sediments deposited immediately after their death. As deposition on the denuded surface of the older formation generally occurs in a basin, either a sea or a lake, with a gently-sloping shore, successive beds of the new formation will extend or transgress further over the older formation than the one below it. This is known as *overlap* (Fig. 28).

Dip and Strike of Beds

When earth movement occurs the beds are tilted or inclined. A knowledge of the amount and direction of the maximum tilting is important for purposes of reproducing the arrangement of the strata on a plan or map, known as a geological map, and in cross-sections showing the probable arrangement of the strata vertically. It is known as the inclination, full or true dip of the strata (Fig. 29), and is the steepest slope the beds make with the horizontal measured in degrees. The direction in which this maximum inclination occurs is referred to the points of the compass. Thus a series of beds when measured by a clinometer (Fig. 30), may have a dip of 8°, in a direction NNE. A horizontal bed will have a dip of 0° and a vertical bed, 90° and the direction of dip will depend on the direction in which the pressure producing tilting or folding was applied. On geological maps the direction and amount of the dip is shown by the following symbol: 8°→. A direction at right angles to the line of full dip of the beds will be horizontal and is known as the direction of the *strike* of the beds. Thus the direction of strike of the beds mentioned above

would run WNW. and ESE. An inclined bed coming to surface on a dead level plain will run across the plain, or *outcrop*, along the direction of strike, and the various beds will appear as a series of bars,

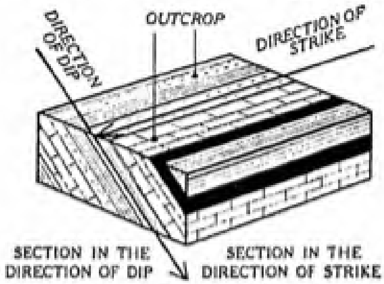


FIG. 29. DIP AND STRIKE

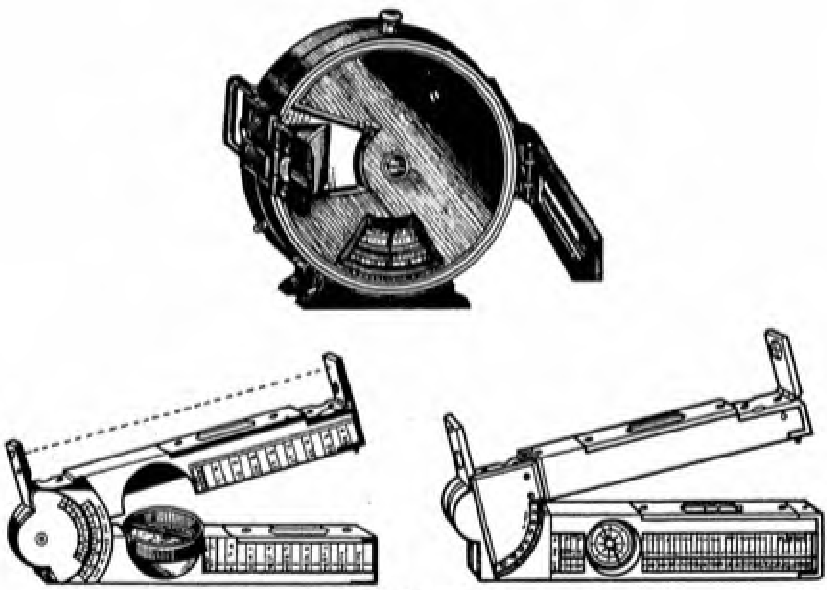


FIG. 30. CLINOMETERS

oldest to the rise in the direction in which the beds are dipping (Fig. 31). If the beds are vertical, the width of the bands at outcrop will be the true thickness of the beds. In other cases the width of the outcrop in relation to the true thickness of a bed will depend on the angle of dip, so that width of outcrop $= \dfrac{\text{thickness of bed}}{\text{sine of angle of dip}}$.

When, however, the surface is not a flat, horizontal plain, but is itself undulating, the shape of the outcrops will depend upon both the dip and the configuration of the surface. Vertical beds will always remain as straight lines and horizontal beds will have outcrops running parallel with the surface contour lines. In valleys

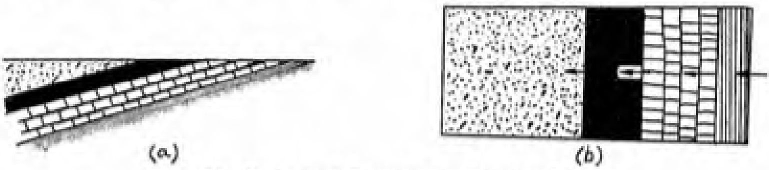


FIG. 31. PLAN AND SECTION OF DIPPING STRATA
(a) Section on line of full dip. (b) Plan of outcrops.

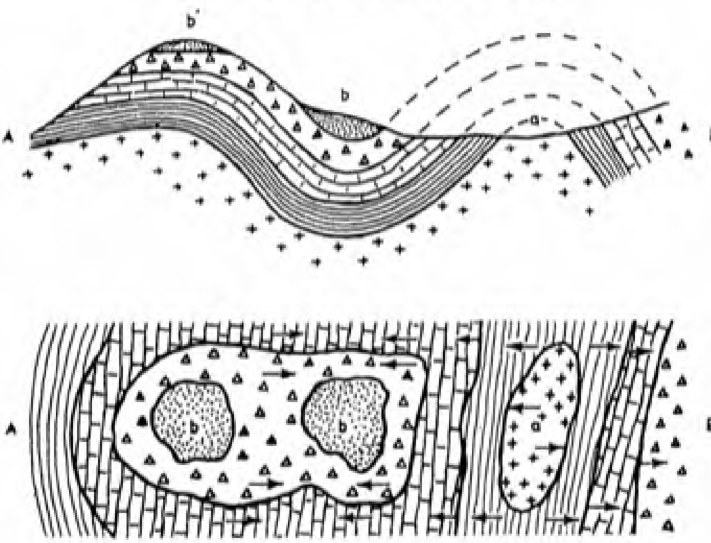
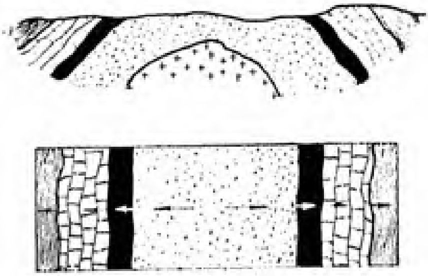


FIG. 32. INLIER *a* AND OUTLIER *b*
Produced by folding with Outlier on hilltop produced by denudation.

beds dipping at a lesser angle than the gradient of the floor of the valley will have a V-shaped outcrop pointing upstream, beds dipping against the gradient of the valley will have a blunt V-shaped outcrop pointing upstream, while beds dipping at an angle greater than the gradient of the valley floor will give V-shaped outcrops pointing downstream. The lower the dip the greater the irregularity of the outcrop. Dips rarely remain constant either in amount or direction, the line of strike of course, changing direction with the dip. If a

patch of older rock is exposed at the bottom of a valley surrounded by new rocks it is known as an *inlier*, *a* (Fig. 32), while a patch of new



(a)

FIG. 33A. SECTION AND PROJECTION OF AN ANTICLINE

(b)

FIG. 33B. ANTICLINE IN LOWER CARBONIFEROUS
Railway Cutting South of Dunbar.
(J. G. C. Anderson)

rock isolated on the top of a hill, surrounded by older strata is known as an *outlier*, *b* (Fig. 32). Inliers and outliers are also produced by folding or crumpling of the beds by pressure resulting from earth movement (Fig. 32).

Folding

When strata are crumpled by pressure, certain types of folds or rucks have come to be recognized, some simple and some, by compounding different types, extremely complicated. The simplest

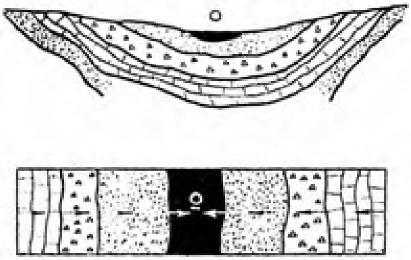


FIG. 34. SYNCLINE WITH OUTLIER, *o*

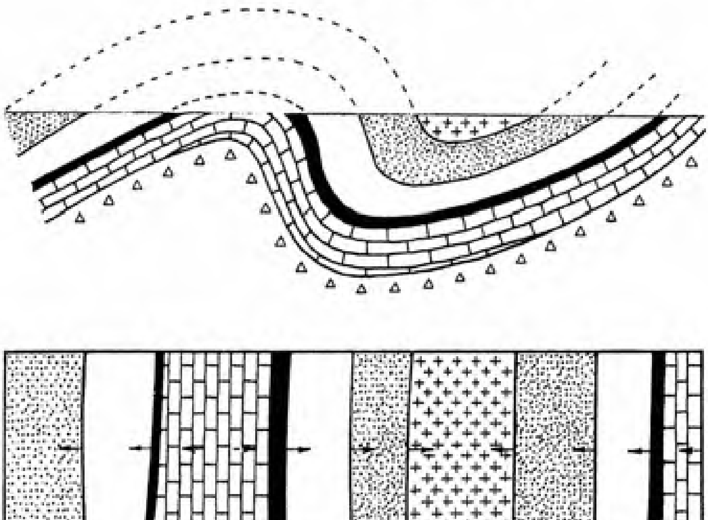


FIG. 35. ASYMMETRICAL FOLD

is the arch or *anticline* (Fig. 33), in which the beds dip in opposite directions away from the line or axis along the summit of the fold, which runs at right angles to the direction of the application of pressure. The direction of the axis is rarely horizontal but is inclined and this is known as the *pitch* of the axis, denoted like the dip by the angle of inclination to the horizontal and compass direction. The

complement of the anticline is the *syncline* (Fig. 34), in which the strata is bent into a hollow or trough and the beds dip towards each other. Folds are rarely symmetrical (Figs. 33 and 34), but one limb is generally steeper than the other, the steeper being on the side away from the direction of thrust, when the fold is said to be asymmetrical (Fig. 35).

The different portions of the fold are known by distinctive names;

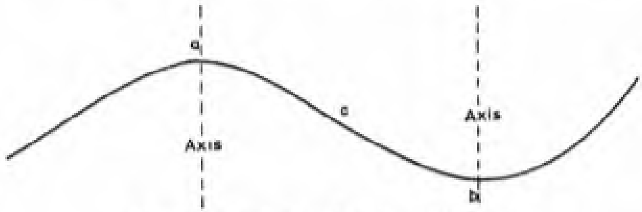


FIG. 36. PARTS OF A SYMMETRICAL FOLD

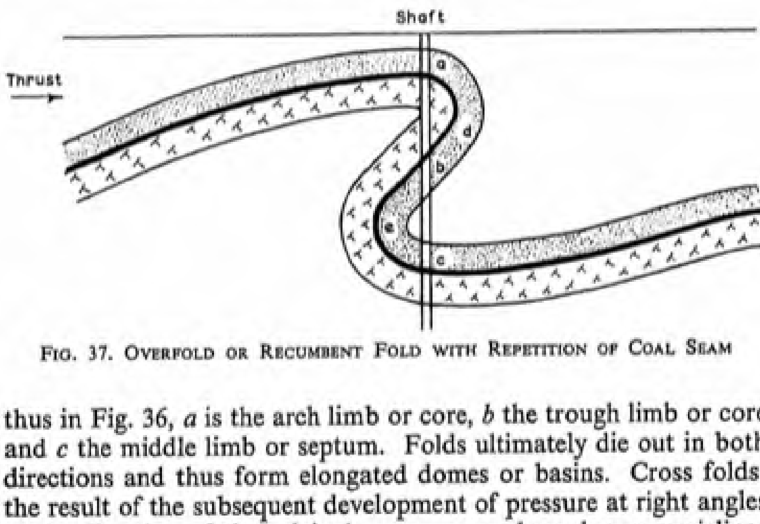


FIG. 37. OVERFOLD OR RECUMBENT FOLD WITH REPETITION OF COAL SEAM

thus in Fig. 36, *a* is the arch limb or core, *b* the trough limb or core and *c* the middle limb or septum. Folds ultimately die out in both directions and thus form elongated domes or basins. Cross folds, the result of the subsequent development of pressure at right angles to the direction of the original pressure, produce domes, periclines and basins in which the beds dip from or to a central point. Generally these basins are again elongated in one direction. The different coalfields owe their escape from destruction by erosion to the basin-like structures in which they now are found.

An asymmetrical fold, when the lateral pressure has been intense, may have the limb away from the direction of pressure application vertical and even overturned (Fig. 37). In such a case a shaft sunk

to recover a coal seam *a* at *c*, may pass through the seam three times, *a*, *b* and *c*, and between *d* and *e* the strata will be *inverted*, the newer strata being under the older. Such a fold is termed an *overfold* or a *recumbent* fold. Instead of being simple, folding may take the form of secondary anticlines or synclines forming together a main anticline or syncline. Such an arrangement is known as an *anticlinorium*

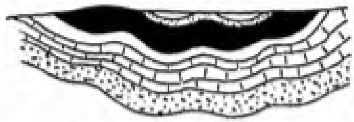


FIG. 38. SYNCLINORIUM

or a *synclinorium* (Fig. 38). The Pennine Range of Derbyshire is an arch of the former type and separates the Lancashire and Yorkshire and Derbyshire coalfields. Reference has already been made to the contorted, complicated folding of the nappe and overthrust types of the Alps and North-West Highlands of Scotland.

Faults

Faults are cracks or dislocations of strata which occur when, owing to the low elastic limit of most rocks, the strains set up by earth movement and folding exceed the resistance of the strata. The beds are displaced on the two sides of the plane of fracture. Two

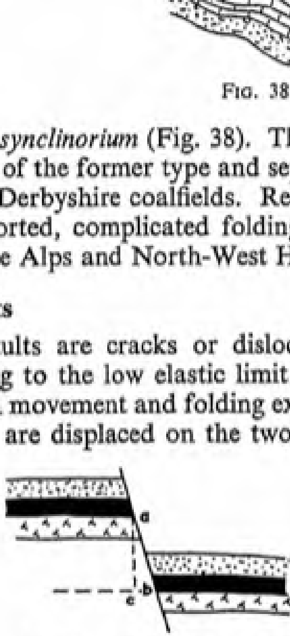


FIG. 39. NORMAL OR TENSION FAULT

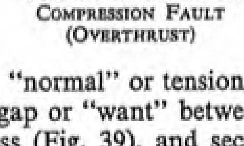


FIG. 40. REVERSED OR COMPRESSION FAULT (OVERTHRUST)

types of faulting are to be distinguished, "normal" or tension faults in which the rocks are stretched and a gap or "want" between the beds allows of the relief of tensile stress (Fig. 39), and secondly, "reversed, thrust or compression" faulting (Fig. 40), in which a bed is thrust over itself and the bed is overlapped or repeated. In Figs. 39 and 40, *ab* represents the plane or crack fissure of the fault which generally dips at a high angle, *abc*, to the horizontal in the case of a normal fault, and at a low angle in the case of a reversed fault. The angle of hade is the complement of this, *bac*, the throw or displacement of the fault is *ac*, the shift or "want" in the case of a normal

fault is *bc* (Fig. 39), the overshift in the case of a reversed fault is *bc* (Fig. 40). In a normal fault the fault plane or slip indicates the direction in which the displaced bed has moved viewed from the other bed. Generally the dip of the beds changes in the vicinity of a fault, being bent upwards in the case of an upthrow fault, from *b* to *a* in Fig. 41, and down in a downthrow fault from *a* to *b*. This is sometimes known as the "drag" of the fault. The direction of the fault

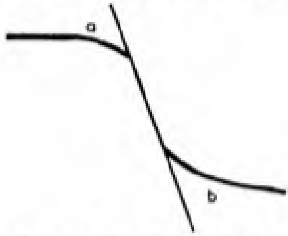


FIG. 41. DRAG OF A FAULT

plane is known as the strike of the fault and this is seldom a straight line for a long distance. Similarly, the dip of the fault plane varies as the fissure crosses beds of different hardness, the angle of dip, like that of the fissure or "draw" produced by mining subsidence, being steeper in the harder rocks. The amount of the throw of faults also varies. Starting from zero it increases to a maximum about the middle of its course and then again falls to zero. Branches or offshoots may split off the main fault and faults may cross each other, the minor being shifted by the other, master, fault. Faults may occur

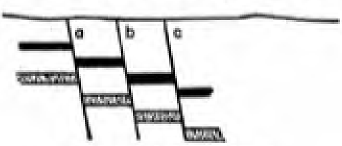


FIG. 42. STEP FAULTS

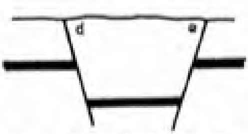


FIG. 43. TROUGH FAULT

in parallel groups, and are then known as step faults (*a*, *b*, *c* Fig. 42). Faults, opposite in throw,.may occur adjacent to each other, so that a given bed is displaced into a trough and then thrown up to its former horizon. This is known as a trough fault (*d* and *e*, Fig. 43).

Faults generally run in one of two directions at right angles. The first group, known as longitudinal or *strike faults*, runs parallel to the strike of the beds and to the axes of the folding. The second group, called transverse or *dip faults*, runs parallel to the dip of the beds. Faults may cause a displacement from a fraction of an inch to thousands of feet.

Effect of Normal Faults on Outcrops

Strike faults cause a repetition of the outcrop of a given bed (Fig. 44), which shows the repetition of the outcrop of a coal seam by two strike faults.

Dip faults cause a shift in the outcrop of a particular bed, as in

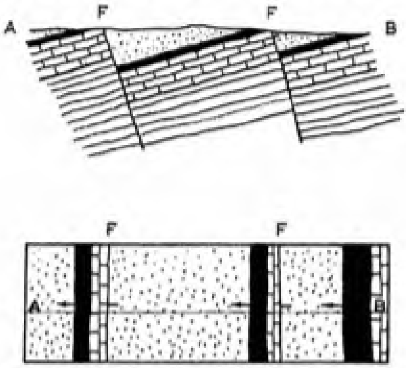


FIG. 44. REPETITION OF OUTCROPS BY STRIKE FAULTS

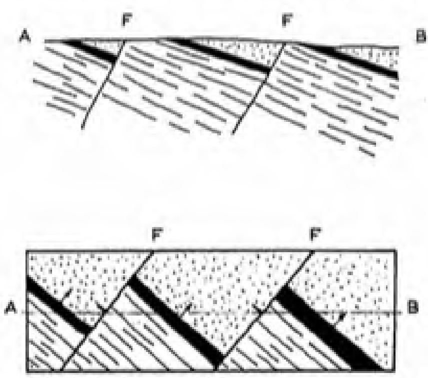


FIG. 45. SHIFT OF OUTCROPS BY DIP FAULTS

Fig. 45, which shows the effect of two dip faults, *F*. The downthrow side of a fault is indicated on a geological map by a short bar on that side of the fault plane, and the throw if known, is shown in yards. The outcrop of a fault at surface is shown in white; where proved underground, in yellow; proved faults by a full line, hypothetical by a broken line.

Fault fissures are rarely visible at the surface and the presence of the fault is indicated by the juxtaposition of beds of different

horizons in the sequence. A sudden discontinuity in surface features would also indicate possible faulting.

Reversed Faults

A reversed fault, the result of compressive forces produced by the movement of material against a foreland of older rocks which forms a buttress or one jaw of a vice, is often the result of the rupture or pinching out of the septum or middle limb of a recumbent fold, as shown in Fig. 46, which shows also the low dip of an overthrust, the type often associated with the building of mountain chains. It will be apparent from Fig. 46 that the overlap or repetition due to a reversed fault may give misleading information in a borehole or shaft as the same seam may be penetrated twice and so give an erroneous idea of the resources available. On the other hand, if bored or sunk into the want of a normal fault in the vicinity of a coal seam, that seam may be missed entirely. Reversed faults are not common in Coal Measure strata in this country.

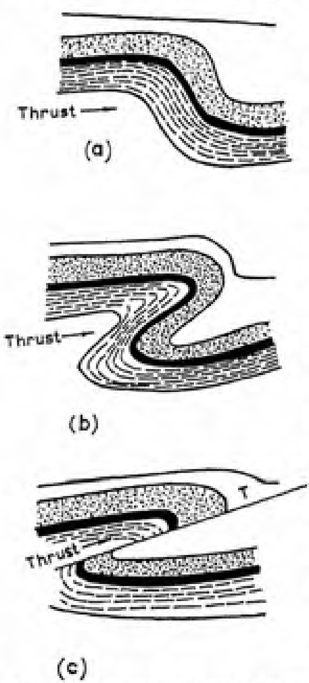


Fig. 46. Stages in the Formation of an Overthrust, T

Fault Fissures

Movement of rocks over other rocks along a fault fissure causes striation and scratching of the rocks in a characteristic fashion producing what is termed a slicken-sided surface. The fissure itself may be a narrow, almost imperceptible crack or a wide belt of crushed material, the width being no criterion of the throw of the fault. It is often lined with a tenacious clay called the leather-bed, leader, selvage or gouge. This also commonly contains crystalline material as faults often form channels for underground water. The ores of metals such as lead, tin, copper and zinc may be deposited in fault fissures (from solution in subterranean water) as veins or lodes. In the same manner dangerous inrushes of water may occur when faults are encountered in underground workings of collieries and mines, particularly if the area is overlain by porous rocks heavily charged with water. Fragments of rock from the sides of the fault fissure may

be found in it, cemented by quartz, calcite or other material into a crush breccia, or if the fragments are rounded by movement along the fissure, a crush conglomerate.

Joints and Cleavage

Related to folding and of importance in mining and quarrying is jointing in rocks, the series of vertical division planes, sometimes at relatively great distances apart and in others much nearer together. They form two sets at right angles to each other, one set parallel to the strike and the other parallel to the dip. Jointing is generally

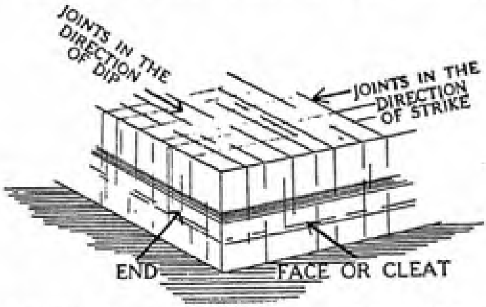


FIG. 47. DIAGRAM ILLUSTRATING THE TERMS, CLEAT, FACE AND END

particularly well developed in all except anthracite coals, and even the smallest particles exhibit two vertical faces at right angles known as "cleat," as well as the normal horizontal banding or bedding. One set is generally more strongly marked than the other and is known as the "bord" or "face" of the coal while the other is known as "end," "headways" or in the United States as the "butt" (Fig. 47). In the days of hand-getting the "cleat" or "cleavage" was of special importance, as coal worked on "bord" was easily got. Other directions at definite angles to the bord and cleat had characteristic names. With the advent of coal-cutting by machinery many coal-faces are "on end" or approximately in that direction, so that the coal is produced in cubical pieces.

In certain coalfields "cleat" is replaced by "slip." In slip the coal has division planes at about 70° to the horizontal so that the coal lies in inclined layers like the leaves of a book. When the layers slope away from the miner, this direction is known as working "on the face of the slips" and coal-getting is easy. Working in the reverse direction with the slips leaning towards the worker is less easy as the coal is more liable to roll over. This is known as working "on the back of the slips."

Cleavage in slates, already mentioned, is also the result of earth movement and particularly of metamorphism but should not be confused with cleavage or cleat in coal seams.

QUESTIONS

1. Give an account of the mode of deposition of the more common types of sedimentary rocks.
2. What do you understand by stratification and lamination?
3. Give some account of the deposition of denuded material in lakes and deltas.
4. Define the following types of sedimentary rocks—

   (*a*) Rudaceous.
   (*b*) Arenaceous.
   (*c*) Argillaceous.
   (*d*) Calcareous.

5. Write an account of the iron-ores of Great Britain.
6. What do you understand by dip and strike of sedimentary strata?
7. Give some account of the common types of folding.
8. Describe, with illustrations, the principal kinds of faults.

CHAPTER V

ELEMENTARY STRATIGRAPHY

BRIEF HISTORY OF THE GEOLOGY OF THE BRITISH ISLES

As sedimentary rocks have been laid down in successive layers it follows that the older will be below the younger unless folding and faulting have produced inversion since deposition. If the folding is unravelled and the strata returned, in the mind's eye, to its original position, this first law of stratigraphy—the science of the sequence of rocks—called the law of superposition which states that of any two beds of sedimentary rock that which was originally below is the older, will enable the beds to be arranged in the correct order of age. This law, of course, applies only to the sedimentary rocks but a further test of age is that of included fragments. That is the rock must be younger than that which supplied the pebbles, sand or mud from which it is built up. Also of importance is the lithological nature of the rock. Rocks of particularly distinctive character, such as coal seams, chalk and red sandstones, may be traced and so correlated over a wide area, but it must not be forgotten that a particular bed may change fairly rapidly in composition, laterally. Thus a coarse sandstone may merge into a stone-bind (siltstone) and then into a shale, so that lithological character is only conclusive in rather exceptional cases. Intrusions, such as sills and dykes, must be newer than the newest sediment into which they are intruded and older than the oldest sediment containing fragments of them. Owing to frequent repetition of sets of physical conditions in different geological ages, deposits of remarkable lithological similarity have been produced differing widely in age and a more certain criterion is that of fossil content of rocks. Meticulous and detailed research work has confirmed the truth of the law, first enunciated by William Smith, that each bed or group of beds is characterized by its own particular set of organic remains. The utility of fossils for purposes of correlation of strata over the widest possible area will, therefore, be appreciated. Evolution is proceeding and has always taken place and each species of organism, plant or animal, flourishes for only a limited period on the earth and then dies out. When it once dies out, that is, becomes extinct, it never reappears. Further, the habitat of the fossil, marine, estuarine or fresh water, is a clue to the

conditions of deposition of the sediment in which it is found embedded.

For purposes of identification and correlation it is evident that a species of fossil, which must have its origin in a particular district and which then spreads rapidly laterally, reaches its maximum distribution in a short space of time and then dies out quickly, as shown diagrammatically in *A* Fig. 48; this species is of more use for identification purposes than one (*B* Fig. 48) with a limited horizontal distribution and a long time range. The desiderata in a fossil are therefore—(*a*) small vertical range; (*b*) wide and rapid distribution, geographically, from its place of origin.

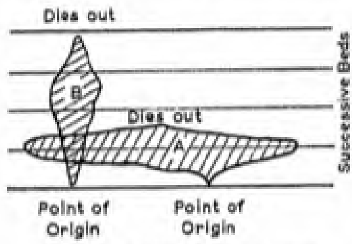


FIG. 48. FOSSIL DISTRIBUTION

It should be realized that a species may withdraw from a particular area through changes in local conditions which become unfavourable to it, but may reappear when conditions again alter. But if it dies out entirely throughout the world and becomes extinct it does not reappear. Great or rapid changes in the fossil content, which is normally gradual from bed to bed, may indicate an unconformity, an incursion of the sea into a lacustrine area or the sudden deepening of the sea. Such changes are of great importance and form convenient division lines between groups of sediment.

PRESERVATION AND CLASSIFICATION OF FOSSILS

Only in recent rocks are the actual hard parts of the dead organisms preserved. Generally there is found only a cast, external or internal, or a hollow cast reproducing both internal and external markings, particularly of shells, but where replacement takes place the organism is replaced particle by particle by another material such as iron carbonate, silica or pyrites and the structure of the original organism is preserved perfectly.

Fossils, like living biological and botanical specimens, need classification if they are to be of any use, and the first division is of

course into animals and vegetation. The animals may be divided into nine phyla.

1. PROTOZOA, the simplest form of life, having no separation of function of the several parts except the hard protective covering or skeleton which forms the fossil. Common examples are the Foraminifera with a calcium carbonate case and Radiolaria with a geometrical covering of silica.

2. PORIFERA are slightly more complex having two layers with tubes traversing the body through which water circulates and into which food is drawn. The sponges with horny, silicious or calcium carbonate framework of spicules belong to this sub-kingdom.

3. COELENTERATA have a separate central canal or cavity for digestion communicating with a mouth equipped with tentacles. They are subdivided into Hydrozoa and Actinozoa. The former includes the Graptolites, one of the most important fossils of the Lower Palaeozoic (ancient life) rocks, which are connected together in line so that the appearance of the composite animal is that of a quill pen. The Actinozoa includes the corals, important as limestone builders.

4. ECHINODERMATA are distinguished by their thorny skins and are much more highly organized than the preceding sub-kingdoms. They are often protected by plates or spines of calcium carbonate and include the star-fishes, sea-urchins and Crinoidea or sea lilies, the last forming the Carboniferous Limestone of the Derbyshire area.

5. VERMES, or Worms, which are not common as fossils unless they are covered by a calcium carbonate tube. Worm casts or tracks, however, have been discovered in terrestrial deposits.

6. ARTHROPODA consist of animals divided into a number of parts in series, each equipped with a pair of legs. It includes Crustacea, like lobsters and crabs, spiders and insects. The most important fossil type is the trilobite which in its various forms lived in Palaeozoic times only. It consisted of segments divided into three portions, the segments are joined to the head with jaws and antennae and the tail and chest portions have feet for swimming and gills for breathing.

7. MOLLUSCOIDEA are animals with soft bodies protected by a shell of calcium carbonate or of a horny texture. The Brachiopods are an important subdivision in which the protection takes the form of a bi-valve shell, with the lower valve, containing the animal, larger than the upper valve. Although differing in size, the valves are symmetrical. Arms or feelers attached to the mouth conveyed food to it and in many cases these arms were supported by a spring-like framework. The Brachiopods flourished particularly in the older, Palaeozoic, rocks but certain forms persist to the present day.

8. MOLLUSCA comprise the shell-fish, with a well-organized and developed corpus and have three important subdivisions. The Lamellibranchs are headless and are protected by a bi-valve, the two shells being similar in size and symmetrical, carried on the sides of the body. The cockles and mussels are present-day representatives. The Gasteropods, on the other hand, have heads equipped with eyes and the single valve protection is conical in shape, simple or spiral as in snails and whelks respectively. The older fossil Gasteropods were vegetable feeders, but the later representatives are often carnivorous. The Cephalopods also have heads, with tentacles to convey food to the mouth. The characteristic feature is a sutured shell divided into septa. The cephalopods reached their maximum distribution in the Mesozoic (Middle Age) Rocks, and among those frequently encountered are *Nautilus*, still extant, and the fossil Ammonites. The cuttle-fish is a modern representative of the fossil Belemnites.

9. VERTEBRATA are relative newcomers in Geological time. The characteristic of this phylum is a skeleton with a backbone and four limbs. Subdivision is into five categories—fish, both salt and fresh-water habitants, which breathe by means of gills and are cold-blooded; amphibia, breathing by gills in their youth and by lungs on reaching maturity; reptiles, cold-blooded and with short or no limbs, but breathing by lungs; birds with the power of flight and coverings of feathers instead of scales or hair; and mammals to which the common land quadrupeds belong. Since the end of the Middle Age, Mesozoic, rocks, there has been a development of the placental mammals and in the last million years, a veritable moment in geological time, the evolution of man has occurred.

The second kingdom is that of the plants; divisible into Phanerogams, bearing flowers and on fertilization produce seeds by which reproduction takes place, and the Cryptogams, without flowers, which include fungi, lichens, mosses, sea-weeds and ferns. The Phanerogams are subdivided into the Gymnosperms, with naked seed, including firs, pines and the cycads and the Angiosperms which include palms, lilies and most of the common garden and hedgerow plants and trees in which the seed is carried in a seed-vessel or container. In Palaeozoic rocks Cryptogams alone are found as fossils, but in Mesozoic rocks Phanerogams appear and Angiosperms are found from the Cretaceous (chalk) period.

Distinct and definite groups of fossils are confined to a single bed or zone, although some may overlap a number of zones but have reached their maximum development and are therefore more numerous in a particular zone.

As breaks in deposition are never world-wide, it is to be expected that in certain cases a strongly emphasized unconformity exists in certain areas between two groups of sediments and in others transition takes place from one to the other without any break in the succession. Thus the break between the Carboniferous and the Permian systems is well marked in this country, but the transition is without a break in the east. It will also be realized that in past ages, as at the present time, marked climatic differences occurred in different parts of the globe and that oceans were divided as now by continents which had each their separate and distinct flora and fauna. Thus exact and easy correlation by fossils over very wide areas is not possible and can only be achieved by progressing from one area to the other in stages.

DIVISION OF STRATA AND GEOLOGICAL TIME

By painstaking research the succession of sediments has been divided first into five main divisions in time, called eras, and the succession of strata deposited during each is known as a group. These are again subdivided into periods (time), and systems (strata), and these again successively into epochs (time), and formations or series (strata); age (time); stage (strata); and phase (time) and zone (strata).

The tendency as knowledge accumulates is towards an increasing subdivision into sub-zones, but although the division outlined above was adopted at the International Geological Conference in 1900, the convention is not always rigidly adhered to by geologists.

The most promising absolute measure of the age of strata appears to depend upon a measure of the helium and lead content of rocks produced by the degradation of radio-active heavy elements. As some helium may have escaped and some lead may have existed in the rocks when laid down, minimum and maximum possible ages are obtained according to which is adopted as the age index. The true age probably lies somewhere between the two. In Table I, which shows the main divisions of the succession, the age and duration of the systems is also indicated, the character of the deposits laid down on land or in the sea and the main systems of folding. The relative thicknesses of strata in the various geological systems are shown in Fig. 49.

The British Isles and Western Europe comprise one of those areas whose geological history is marked by a cyclic repetition of alternations of earth movement associated with emergence and mountain-building and submergence accompanied by sedimentation. The sediments are generally of a marine type associated with deposition

in a shelf area bordering a continental shield. The geological succession available for study is therefore very complete in contrast to the more stable portions of the earth's crust.

Era (Group)	Period (System)	Epoch (Formation)	Age (Millions of Years)	Duration (Millions of Years)	Character of Strata	Folding and Direction
QUATERNARY	Recent	*Soil and Alluvium*	1	1	Continental	—
	Pleistocene	*Boulder Clay, sand*			Continental	—
TERTIARY	Pliocene Miocene	*Cromer Forest* *East Anglian Crags* *Not present in Great Britain*	20	19	Continental	Alpine E–W
	Oligocene Eocene	*Isle of Wight Marls and Limestones* *Bagshot Sands* *London Clay* *Thanet Sands*	55	35		
MESOZOIC	Cretaceous	*Chalk, Gault* *Lower Greensand* *Weald Clay and Sands)*	105	50	Marine	
	Jurassic	*Purbeck and Portland* *Kimmeridge Clay* *Oxford Clay* *Bath Stone (Gt. Oolite)* *Lincs. Limestone (Inf. Oolite)* *Northants Ironst* *Lias*	145	40	Marine	
	New Red Sandstone: Trias	*Keuper* *Bunter*	175 205	30 30	Continental	Armorican E–W Pennine N–S
	New Red Sandstone: Permian	*Magnesian Limestone* *Penrith Sandstone*			Continental	
UPPER PALAEOZOIC	Carboniferous	*Coal Measures* *Millstone Grit* *Yoredale Beds* *Carboniferous Limestone*	285 335	80 50	Continental Marine	
	Devonian	*Torquay Limestone* *Old Red Sandstone*			Continental	Caledonian NE–SW
LOWER PALAEOZOIC	Silurian	*Downton Sandstone* *Ludlow Shale* *Wenlock Limestone* *Llandovery Sandstone*	375	40	Marine	
	Ordovician	*Bala Series* *Llandilo* *Arenig*	425	50		
	Cambrian	*Tremadoc* *Lingula Flags* *Menevian* *Llanberis Slates* *Basal Quartzite*	485	60		
PRE-CAMBRIAN	—	*Torridonian* *Uriconian* *Lewisian*	2,000	1,500		Huronian NW–SE

Pre-Cambrian

The oldest rocks encountered in the crust are those which constitute the massive cores of the continental shields and are called, for the want of a better name, the Pre-Cambrian since they are older than the Cambrian, in which the first fossils are found. As the latter are relatively highly developed the lapse of time between the two must be very large, and since no fossil trace of this period is available

except somewhat doubtful worm-casts in the Huronian series of Canada and phosphatic lenticles in the Torridonian of NW. Scotland, it seems likely that life first appeared in the seas and left no trace, although the destruction of fossil evidence by intense earth movement and metamorphism cannot be ruled out.

The Pre-Cambrian rocks are divisible into two systems, the Archaen and the Algonkian. These are represented in NW. Scotland, the area in the British Isles in which the extensive exposure of Pre-Cambrian rocks occur, by the Lewisian gneisses and Torridonian Sandstone series respectively. Elsewhere in Britain a volcanic series of lavas and ashes divides the Lewisian and Torridonian facies.

FIG. 49. RELATIVE THICKNESSES OF ROCKS OF THE VARIOUS GEOLOGICAL SYSTEMS

The length of the period of time which each system represents is not always proportional to the thickness of the rock included in it.

The older portion of the Pre-Cambrian has been named the "Fundamental Complex" and into this has been intruded a series of dykes and sills of igneous rocks. Earth movement has metamorphosed the complex, which largely consists of plutonic rocks, into gneisses together with some sediments now metamorphosed into schists and even the intrusions into these show metamorphism in the shape of foliation and banding. All vary in composition from ultra basic to acid, the former being probably the earlier. The Torridonian series is stratified and often horizontal, resting unconformably on the highly-contorted and deeply-weathered surface of the Lewisian series. It consists of coarse grits and arkose, reddish-brown in colour with much felspar and interbedded shales. It was deposited quickly and shows false bedding, and is presumed to have been laid down by torrents in a semi-arid region.

Elsewhere in the British Isles small patches of Pre-Cambrian occur as in Anglesey, Pembrokeshire, the Longmynd of Shropshire, the Malvern Hills, Lilleshall, Burnt Green, the Lickey Hills and near Nuneaton (Fig. 50). Those in England are of the volcanic facies and are termed Uriconian and Charnian, with the exception of the Longmynd which consists of nearly 30,000 ft of sedimentary rocks of

green, grey and purple shales and flags, and red and purple conglomerates. It is clear that NW. Scotland was land during Pre-Cambrian times, and this land extended into Norway. The southern limits of the continent of which it formed a part are uncertain, but

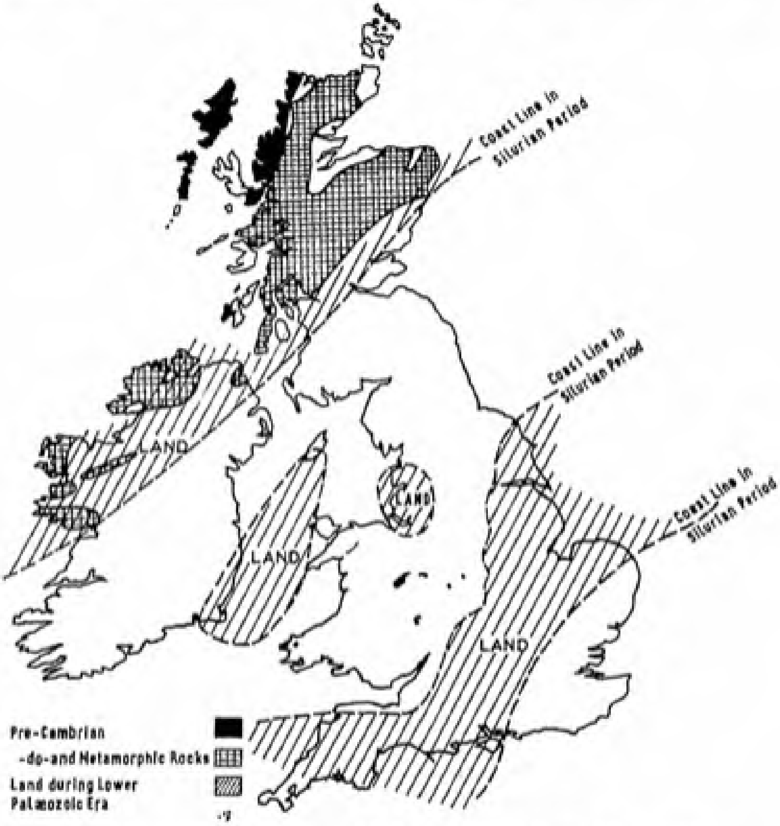


FIG. 50. PRESENT OUTCROPS OF PRE-CAMBRIAN ROCKS—SOLID BLACK PRE-CAMBRIAN AND METAMORPHIC ROCKS—CROSS HATCHED; ALSO DISTRIBUTION OF LAND AND SEA IN THE SILURIAN PERIOD

appears to have included the Longmynd. The Pre-Cambrian represents a period of 1,000 to 1,500 million years with an unconformity between the Lewisian and the Torridonian representing an enormous time interval and several periods of intense earth-movement. Elsewhere than in the British Isles, the Pre-Cambrian is characterized by the richness of its mineral deposits.

The Cambrian, Ordovician and Silurian Systems

It is convenient to consider together these three systems, comprising the Lower Palaeozoic some 200 to 300 miles in width running across Britain from SW. to NE. to Scandinavia (Fig. 50), with local, minor unconformities through crustal warping, deposition to a total thickness of some 40,000 ft, took place. At the beginning, in the Cambrian, the NW. coast of Scotland formed the shore of a second ocean related to North America, but this shifted to the NW. in Ordovician times. The deposits differ in having calcareous rocks in the succession. The Cambrian marks the beginning of the fossil record and as most of the families of animals, except the vertebrates, were represented and development had already progressed considerably, it is thought that more primitive forms must have developed in the sea under conditions inimical to fossil preservation.

The Cambrian lies unconformably on the Pre-Cambrian and in the same localities—North and South Wales, Shropshire, the Malverns, Nuneaton, the Lakes and the NW. Highlands. The Cambrian consists of sandstones and shales often converted to quartzites and slates by dynamic metamorphism associated with the Caledonian orogenic movement which originated in Scotland in Silurian times, reached a peak in the Devonian and died out in Carboniferous times. It folded, crushed and thrust the rocks of the geosyncline and piled them up in such a manner as to have great subsequent influence on the structure of the British Isles.

The base has grits and conglomerates indicating deposition near the shores on each side of the gulf and as this widened later, they are succeeded by mud-belt deposits. Four main divisions of the Cambrian are associated with main groups of the characteristic fossil, the trilobite, a crustacean, *Olenellus* (Fig. 51), *Paradoxides*, *Olenus* and *Shumardia*, the latter being sometimes included with the Ordovician. In the region in which the exposure is most extensive the succession is (*a*) Lower Harlech beds consisting of grits and shales (*b*) the Upper Harlech and Menevian Beds, also grits and slates (*c*) the Lingula flags consisting of flags and slates (*d*) the topmost—the Tremadoc Slates.

The Cambrian system was terminated by uplifting and gentle folding marking the unconformity between this and the next system, the Ordovician, so called after an ancient Celtic tribe, the Ordovices who inhabited the region of East Wales and Shropshire in which the typical exposure occurs. The system is characterized by evidence of much submarine volcanic activity as shown by lavas, ashes and tuffs interbedded with shelly, sandy and calcareous marine deposits

containing brachiopods and trilobites and with slates and shales containing graptolites (Fig. 52). The three types of rock, volcanic, shelly and graptolytic, occur simultaneously, the type of deposit depending on the proximity of the shore-line, the shelly near the shore from which a plentiful supply of material from rivers was provided and the graptolytic, of finer material, further off-shore. As with the Cambrian the thickness of the littoral deposits near the

FIG. 51. A TRILOBITE FROM THE CAMBRIAN ROCKS OF PENNSYLVANIA
Olenellus thompsoni. Natural size.

shoreline is considerable amounting to about 10,000 ft as in North Wales, while in the axis of the geosyncline the graptolytic equivalent only amounts to about 100 ft as at Moffat. In South Wales the system has been divided into five divisions, the Arenig grits and sandstones, the Llanvirn shales with tuffs and lavas, the Llandilian sandstones, calcareous flags, black shales or slates with lavas and tuffs, Caradocian of the same type followed by the Ashgillian (Lake District) of sandy limestone followed by blue-grey and greenish shales. As well as in the type area Ordovician rocks are exposed in the Snowdon syncline in North Wales, in Shropshire and in the Lake District. They include also lavas (andesites and rhyolites), ashes and volcanic agglomerates, amounting to thousands of feet, as seen in the Borrowdale Beds, the Southern Uplands of Scotland, in a narrow belt near Belfast Lough and in a few other small exposures in Ireland and a small exposure in Cornwall.

The Ordovician is succeeded by the Silurian composed of a similar

series of rocks divisible again into shelly and graptolytic shale types. The former contains thicker and more pronounced calcareous rocks, as in the Wenlock limestone, but the distinction between the two phases is less marked than in the Ordovician. Towards the end of the system the red upper deposits of the Downtonian usher in the terrestrial deposits of the Old Red Sandstone, indicating that the geosyncline was filling up, although south of the Bristol Channel

FIG. 52. ORDOVICIAN GRAPTOLITES: *Didymograptus murchisoni* (BECK) FROM THE LLANVIRN BEDS OF ABEREIDY BAY, PEMBROKESHIRE; NATURAL SIZE

marine conditions persisted during the contemporaneous Devonian system.

In the shelly deposits the fossils are chiefly brachiopods, trilobites, corals and crinoids. Graptolites are common in the shales and the system has been zoned into over twenty graptolite zones. The main lithological divisions are only four—

Downton Grey and Red Sandstones
Ludlow sandstones and shales
Wenlock Grits and shales with limestones
Llandovery Beds of shelly beds with brachiopods and shales with graptolites

Graptolites become extinct in the Downton sandy beds, and vertebrates appear for the first time in the form of fishes in the Ludlow series.

The principal outcrops of the Silurian are in North Wales and the Welsh borders with inliers in the South Staffordshire coalfield, the southern portion of the Lake District, the southern portion of the

Southern Uplands of Scotland, and in Ireland in the west, north and the east. As with the Ordovician the thickest deposits are on the shore lines of the geosyncline, the northern shore being north of the Southern Uplands of Scotland and the southern through South and Central Wales and the Welsh borders, while along the axis of the geosyncline through Moffat the shales are thin until, near the end of the system, sedimentation shifted to the centre of the trough where coarse grits and sandstones were deposited with brackish-water fossils in the Upper Downton phase.

The Lower Palaeozoic, comprising the Cambrian, Ordovician and Silurian systems, lasted for a period of some 150 million years.

The Old Red Sandstone and Devonian System

In the preceding era deposition of sediments, though extremely variable in thickness and dependent upon proximity to a shore-line, extended over a considerable portion of the British Isles. In contrast the deposition during this system was partly marine (the Devonian) and partly terrestrial (the Old Red Sandstone) and in the latter was discontinuous and occurred in semi-arid conditions in which periodic torrential rains scoured rock waste from high ground and spread it out in vast fans over the flat lowlands and in steep-sided rift valleys.

The marine phase, the Devonian, was laid down south of a shore-line extending east and west from the Bristol Channel, and consists of dull-coloured sandstones, slates and limestones of evident marine origin with a fauna of brachiopods, trilobites and corals. They are exposed in Cornwall, South Devon, in North Devon and West Somerset; and are divisible into the Lower Devonian series of slates and grits with some interbedded volcanic rocks, the Middle Devonian also of slates with fewer grits, but many more interbedded volcanic tuffs and a considerable thickness of limestones, the Upper Devonian of massive, grey limestones, and red slates. The Devonian forms a synclinorium of Armorican origin with the axis running east and west through the London area. Though overlain by newer deposits except on the flanks, its presence has been proved under the London Basin by deep bores and it continues into France and Belgium where exposure again takes place. The Old Red Sandstone, on the other hand, consists of brightly-coloured red and brown sandstones and marls with plant remains, ferns and lycopods, and primitive fishes—some of which were air-breathing as well as gill-breathing—which lived in the transient lakes of the intermontane basins. The rocks therefore are of terrestrial or fresh-water origin and the continent on which they were laid down would appear to stretch to the north of

the Bristol Channel. Those in the lower division of the Old Red Sandstone of South Wales and the Welsh Borders appear to have been laid down under shallow marine conditions and still further north, under deltaic conditions. These were followed by an uplift produced by the Caledonian upheaval during which the Middle division of the Old Red Sandstone was not deposited, producing a non-sequence, followed by sandstones of the Upper Old Red Sandstone with fish remains and fresh-water fossils. This continent included the Baltic, Spitzbergen and Greenland and must have extended over a wide area. In the Orkneys and Shetlands the fresh-water flagstones and shales with slight traces of volcanic activity indicate the existence of a large lake or inland sea in this area. In the north of England several small patches of red conglomerates occur in Yorkshire, Westmorland and Cumberland. In Scotland exposures of large extent occur in the Cheviots, the Midland Valley (Forth and Clyde) and in Argyll. As in Wales, the Middle division is absent and the non-sequence is marked by a pronounced unconformity between the Lower and Upper divisions. The Midland Valley was a steep-sided rift valley bounded by faults and filled up by red terrestrial deposits from the region of the Highlands on the north bank and the Southern Uplands on the south. Volcanic activity is very strongly marked by olivine-basalts, basalts and andesites with a widespread development of dykes and sills. The Lower Division here reached its maximum development and accumulated to a thickness of 20,000 ft of sandstones, flags, marls, grits and thick conglomerates and pebble beds. The Upper Division is composed of similar rocks which attain a maximum thickness of 3,000 ft with no volcanic rocks. In Ireland the Old Red Sandstone was deposited in two zones representing continuations of the Welsh deposits in Munster and of the Scottish deposits in Tyrone and Fermagh.

The Old Red Sandstone period is of great importance through the development of the climax of the Caledonian Earth Movement or Revolution. The overthrusts of the Scottish Highlands and Norway and the development of the folding of the Lower Palaeozoic rocks of Scotland, the Lake District and North Wales along NE.–SW. axes, accompanied by volcanoes and intrusions occurred in this period. Granite masses were intruded in Caithness and Sutherland, in the Aberdeen region, in the Western Highlands at Rannock Moor, Ballachulish and Ben Nevis, in the Lakes at Shap, Skiddaw and Eskdale and in Donegal, Sligo, Mayo, Galway and Leinster in Ireland. The lavas of the Ochil and Sidlaw Hills, Edinburgh and the Cheviots represent the extrusive, volcanic phase which continued into the next period, the Carboniferous.

The Devonian and Old Red Sandstone is in many places conformable with the Silurian below and passes up conformably into the Carboniferous above in South Wales, the Bristol area and in Scotland.

QUESTIONS

1. Give some account of the use of fossils in determining the age of rocks.
2. Construct a table showing the main eras and periods of the succession of strata in the British Isles.
3. What do you understand by a "continental shield"?
4. Write an account of (*a*) The Silurian Rocks of Wales, (*b*) The Devonian Rocks of the South of England.

CHAPTER VI

THE CARBONIFEROUS SYSTEM

THIS system is of great importance to the British coal-mining engineer as it contains in the upper division the Coal Measures, the most important source of coal in these islands although coal in seams of workable thickness is found in both older and commonly in newer systems in other parts of the world.

The Carboniferous is generally divided into two divisions—the Lower Carboniferous (Dinantian) and the Upper Carboniferous, with the division line fixed by fossil content. The more customary division in this country is into Coal Measures, Millstone Grit and Carboniferous or Mountain Limestone, in descending order.

THE LOWER CARBONIFEROUS

The characteristic rocks of the Lower Carboniferous are those organically formed (from corals, crinoids (Fig. 53) and brachiopods) and those chemically precipitated limestones deposited in the relatively shallow waters of the southern Pennine area in lagoon conditions, south of the deltaic conditions existing in Northumberland and Scotland, fringing the northern land-mass of the Old Red Sandstone period, in which sandstones, shales and coal seams were laid down. The marine conditions of the Devonian Period continued below the Bristol Channel during the Carboniferous Period and in Devonshire radiolarian cherts, calcareous shales, black limestone and impure coal, known as culm, are to be found. The Upper part of the measures containing these culm bands probably corresponds with part of the Upper Carboniferous elsewhere, the remaining rocks are of the Lower Carboniferous.

In the Bristol area and in South Wales the Lower Carboniferous is composed in ascending order of shales, limestones, shales, limestones, shales and finally Millstone Grit. It decreases in thickness to the north thinning out against an ancient island belt or ridge of land, known as St. George's Land (Figs. 54 and 55), which remained land during Lower Carboniferous times so that the Upper Carboniferous in parts of the South Staffordshire and Warwickshire Coalfields rests directly on Silurian or older rocks.

On the other side of the ridge, the Lower Carboniferous increases rapidly in thickness to the north and reaches its maximum

development in Derbyshire where the limestone reaches a thickness of 1,500 ft. Evidence of volcanic action is afforded by lavas and tuffs,

FIG. 53. FOSSIL CRINOIDS, *Woodocrinus macrodactylus* (DE KONICK)
From the Carboniferous Limestone of Yorkshire; about half natural size.

known as "toadstones" and the mineralization of this area, with lead and fluorspar as economic products, has already been remarked.

Above the limestone come the Limestone Shales. North of the Peak district of Derbyshire, Millstone Grit, generally grouped with

the Upper Carboniferous, covers the Lower Carboniferous but it reappears in the region of the Craven Fault and is exposed to the Scottish Border. The base is formed of the Great Scar Limestone with the Yoredale Beds, consisting of alternations of limestones,

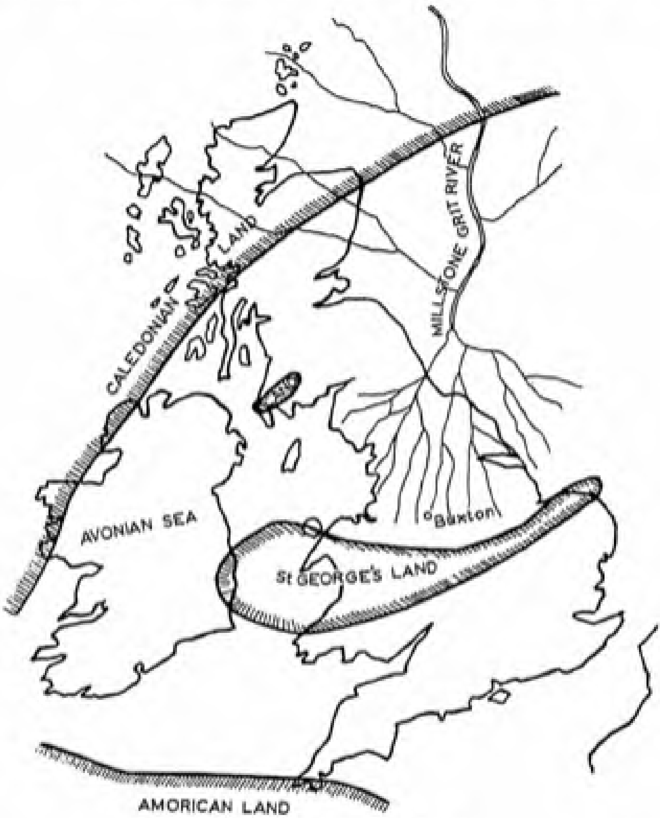


FIG. 54. ST. GEORGE'S LAND

shales and sandstones repeated in that order again and again. A dolerite sill, the Great Whin Sill, has been intruded over an area of some 1,500 square miles of Northumberland, Durham, Yorkshire, Westmorland and Cumberland. It transgresses the beds of the Lower Carboniferous and attains a maximum thickness of 150 ft. It is quarried for roadstone at Stanhope, County Durham.

Further north the Lower Carboniferous becomes less calcareous and consists mainly of sandstones and siltstones with workable coal

seams exploited in Teesdale and at Scremerston in Northumberland. In Cumberland the succession consists of seven beds of limestones followed by shales, grits and subsidiary limestones. The Lower series contains the haematite replacement deposits.

The Lower Carboniferous of Northumberland is divided into the lower or Tuedian series and an upper Bernician series as follows—

BERNICIAN: Upper Bernician (Calcareous Group) of sandstones and shales, shallow marine limestones and coals, from 1,000 to 4,000 ft. Lower Bernician (Carbonaceous Group) of sandstones and shales, thin calcareous beds and many coals (Plashetts Group in the south and Scremerston Group in the north), from 800–1,500 ft.

TUEDIAN: Fell Sandstones of thick sandstones and shales, from 600–2,000 ft. Cementstone Group of shales and sandstones, cementstones and dolomitic limestones from 500–3,000 ft.

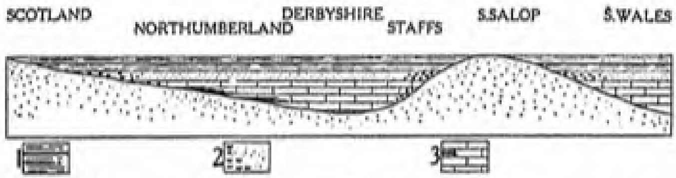


FIG. 55. DIAGRAMMATIC SECTION ILLUSTRATING THE DEPOSITION OF THE CARBONIFEROUS ROCKS

During Carboniferous Limestone times, there were two main areas of deposition separated by a land ridge (St. George's Land). Later, Carboniferous sediments encroached upon the ridge and the Coal Measures were in places deposited over it. The Carboniferous strata become thinner as the buried ridge is approached.
1. Coal Measures. 2. Millstone Grit. 3. Carboniferous Limestone. (Not to scale.)

The exposure terminates at Berwick.

In Scotland the Lower Carboniferous rocks reappear in the Central Valley in which they rest comformably on the Old Red Sandstone. The Lower Carboniferous occupies the centre of the syncline between the parallel outcrops of the Old Red Sandstone. As this region fringed a northern land mass limestones are much thinner than in the English Midlands but volcanic rocks, chiefly basalts, have spread over large areas. The area was slowly subsiding.

The succession is as follows, in descending order—

Carboniferous Limestone Series	Upper Limestone Group Lower Limestone Group with Edge Coals
Calciferous Sandstone Series	Oil Shale Group Cementstone Group

The Cementstones consist of an alteration of shales and impure dolomitic limestones such as would be deposited in inland seas and lakes subject to drying-up. On burning they provide a fairly good

cement and contain a few fresh water fossils although conditions would not be favourable to a flourishing fauna.

The Oil Shales consist of fine black or dark-brown muds and silts impregnated with organic and carbonaceous material of both plant and animal origin, which when subjected to high-temperature distillation with steam gives crude oil which on further fractional distillation produces lighting, lubricating and cleansing oils and ammonium sulphate. At the end of the Calciferous Sandstone period subsidence was accelerated and submergence converted the area from one of lacustrine deposition to shallow marine conditions. The

FIG. 56. A FOSSIL BRACHIOPOD, *Productus gigantus* (MARTIN)
From the Carboniferous Limestone of Llangollen, N. Wales; about one-third natural size.

Lower Limestone group consists at first of shales and limestones with a few thin coals but the upper portion, after the central area had been silted up, consists of alternations of sandstones, shales, fireclays, ironstones and the important Edge coals of Midlothian, including the most important of the Scottish coal seams.

The Upper Limestone Group consists of sandstones, limestones and a few thin coals.

In Ireland the exposure of Lower Carboniferous rocks is very extensive and shows a similar transition from marine to lacustrine and deltaic conditions from south to north encountered in Great Britain. In Antrim ten bituminous and anthracitic coal seams, and three black-band ironstones, occur in a syncline at Ballycastle.

The fossil content of the Lower Carboniferous is rich and important. Of the brachiopods *Productus* is characteristic (Fig. 56), but lamellibranchs and gasteropods are plentiful. Cephalopods include *Orthoceras* and *Goniatites*, *Glyphioceras* and the surviving trilobites, including *Phillipsia*, make their last appearance. The first amphibians, Labyrinthodonts, make their initial appearance in the Lower Carboniferous.

THE UPPER CARBONIFEROUS AND THE COALFIELDS

The Upper Carboniferous is comprised chiefly of sandstones, shales and coal seams. The rocks are mainly of terrestrial or fresh-water origin, but marine bands, marking incursions of the sea, are fairly common.

The Armorican-Hercynian folding which occurred during Permo-Carboniferous times and in which the axes of the folding was in an east-to-west direction in the Midlands from pressure to the south, and north and south in the northern Pennine Uplift, due to pressure from the east, is responsible for the preservation of the Upper Carboniferous rocks in the synclines, or more properly "basins," in which they, and particularly the coalfields, now occur. These basins of Upper Carboniferous rocks occur in (*a*) The Devon syncline, (*b*) The Armorican group comprising the South Wales, Somerset and Gloucestershire Coalfields and the concealed (covered by later rocks) Dover Coalfield, (*c*) The Midland group including the South Staffordshire, Warwickshire and Leicestershire Coalfields, (*d*) The Northern group comprising the Derbyshire, Nottinghamshire and Yorkshire, the North Staffordshire, North Wales, Lancashire and Cumberland and the Durham and Northumberland coalfields, (*e*) The Scottish group, (*f*) The Irish group of relatively small patches including a southern exposure in Clare, Limerick and Kerry, the Leinster basin and several small basins in Leitrim and Tyrone.

The termination of the Lower Carboniferous was marked by a somewhat abrupt change in conditions. An extensive uplift occurred with a renewal of active erosion on the newly-emerged land surfaces, and rejuvenation of river systems. Coarse, thick-bedded, massive grit banks were laid down under deltaic conditions interbedded with much shale, giving the Millstone Grit which reaches its maximum development in Derbyshire, a thickness of 3,000 ft. Felspar pebbles in the Grit are characteristic. The edges or escarpments of the different bands of Millstone Grit, for example the Kinderscout Grit in the middle and the Rough Rock at the top, give rise to the rugged moorland scenery associated with the Derbyshire Moors of the Peak District. Subsidence at a greater rate than sedimentation allowed the deposition of muds in shallow-water conditions, sometimes estuarine but mainly marine, which have since hardened to the shales of which there is a high proportion in the Millstone Grit formation. This was succeeded by the true Coal Measures period, during which general subsidence took place, but in a series of rhythmic stages, with pauses during which the Coal Measure forests flourished. Each pause was terminated by a rather sudden renewal of subsidence,

during which the binds and shales forming the roofs of the coal seams were deposited, this being followed in turn by subsidence at a reduced rate which allowed silting up by sandy deposits to occur, forming deltaic swamps on which Coal Measure forests again flourished (Fig. 57). Clay-ironstones are also frequent.

This cyclic sedimentation was occasionally interrupted by marine incursions, which occurred over large areas, particularly during

FIG. 57. A SWAMP IN A COAL MEASURE FOREST
With *Calamites* in the foreground and from left to right, *Cordaites*, *Sigillaria*, Pteridosperms (in the distance), and *Lepidodendron*.

Lower Coal Measure times. Bands of shale and limestone were deposited during these interludes, known as marine bands, and in these marine fossils occur which render the bands of great importance in the correlation of the different coal seams. In the Middle Coal Measures these invasions become increasingly rare, and the dominant animal fossils used for correlation are the so-called "mussel bands" of fresh-water lamellibranchs. Occasionally fish and amphibia are also encountered.

In the Upper Coal Measures, continental conditions became established through uplifting and folding. The area became converted to a series of land-locked basins; semi-arid climatic conditions prevailed, producing red and green-coloured rocks containing iron peroxide colouring matter, and the Coal Measure forests ceased to flourish except in the Radstock area. Although a variation in the

Upper Carboniferous succession occurs from north to south, as in the Lower Carboniferous, so that the same type of sediment, or same facies, occurs at different horizons in the succession, there was not a continuous migration of maximum coal-formation conditions southwards, from the Lower Carboniferous in Scotland, through the middle of the Upper Carboniferous in northern England to the higher divisions in central and southern England.

It is now considered that the Lower Carboniferous coal measure facies in Scotland was an isolated occurrence and the greatest concentration of workable coal seams occurred in the Middle Coal Measures in all the more important coalfields, during which period uniform conditions must have existed over a wide area. This period would appear to have been terminated by an incursion of the sea marked by the important marine band known as the Mansfield Marine Band in the East Pennine Coalfields, but with equivalents in other fields. In many fields the number of workable seams above this band is not large.

The generally accepted succession, on the coalfields, is divided into four series, in descending order—

Upper Coal Measures
Middle Coal Measures
Lower Coal Measures
Millstone Grit

Although this may suffice lithologically, fossil zoning indicates that it cannot be accepted in time, as in certain cases the Millstone Grit contains Coal Measure fossils. The lamellibranchs are used for purposes of accurate division into seven zones and plant remains have been used to divide the Upper Carboniferous again into four divisions, in descending order—

Radstockian
Staffordian
Yorkian
Lanarkian

These do not, however, always correspond with the practical coalfield subdivision previously mentioned. The Millstone Grit is sometimes called Lancastrian owing to its thickness in that county.

In order to visualize the types of Coal Measure plants which contributed to the formation of coal seams it is necessary to commence with a deltaic or estuarine area from which the sea has been excluded by mud or sand-banks resulting in brackish or freshwater conditions. Under these conditions water-loving plants with the

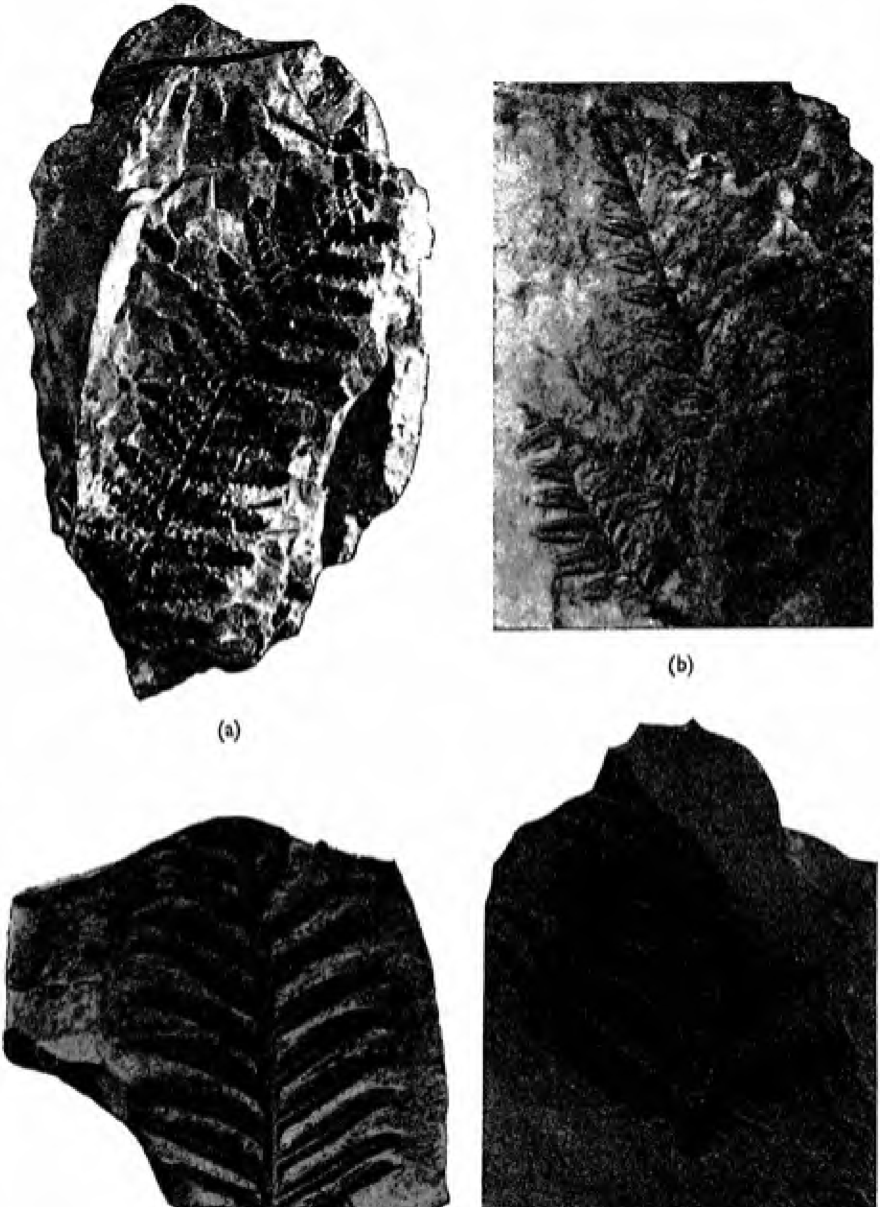


FIG. 58. FOSSIL PLANTS FROM THE COAL MEASURES (PTERIDOSPERMS)

(*a*) *Neuropteris rarinervis*, Bunbury, Blackbrook Colliery, Caerphilly (about one-quarter natural size). (*b*) *Mariopteris nervosa* (Brongniart) in ironstone, Monmouthshire (slightly reduced). (*c*) *Alethopteris lonchitica* (Schlotheim), Soap Vien Ironstone, Abercarn (about one-half natural size). (*d*) *Pecopteris miltoni* (Brongniart), Pentre Seam; *Ex David Davies Collection* (slightly reduced).

roots and base of the trunks submerged would make an initial appearance on the silty banks. These would be of the Calamites and Sigillarian types, and would provide humus and condition the soil for a richer type such as the giant Lycopods, *Lepidodendron*, *Bothrodendron* and *Ulodendron*. On the remains of these fern-like plants formed a thick undergrowth. These included *Neuropteris*, *Mariopteris*, and true ferns including *Botryopteris* and *Asterotheca*.

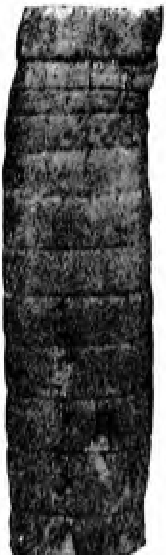


FIG. 59. *Calamites approximatus* (STERNBERG)
Part of a Stem, about one-third natural size.

As the peaty layer produced by the disintegration of the vegetation increased in depth, further change in conditions of drainage and depth of soil would take place resulting in changes in plant species. This is reflected in the banded composition of the majority of seams, which often have a dull soft band at the bottom with much finely comminuted plant debris, followed by bright coal with larger fragments of bark and with spores. The top portion is again dull coal, often full of megaspores, microspores and plant fructifications. Above the seam proper bands of highly carbonaceous shales, "batts," or impure coals with high ash content and perhaps sapropelic coals (or cannel coals) indicate the renewal of subsidence and the deposition of the muds which form the roof of the coal seam.

The following are some of the common plants of Coal Measure Age—

Pteridosperms—*Lyginopteris*, *Pecopteris*, *Alethopteris*, *Callipteris*, *Mariopteris* and *Neuropteris* (Fig. 58).

Articulates—*Calamites* (Fig. 59) and *Sphenophyllum*.

Lycopods—*Lepidodendron*, *Sigillaria*, *Ulodendron*, *Bothrodendron* and *Stigmaria* (Roots) in the seat-earths or clunches below the seam (Fig. 60).

Ferns—*Psaronius*, *Asterotheca*, *Botryopteris* and *Botryocylon*.

Gymnosperms—*Cordaites*, *Dioonites*, *Walchia* (Coniferous).

The character of the Upper Carboniferous in the areas in which exposures exist are as follows—

The Devon Basin is characterized by the occurrence of a soft coal known as "Culm," in a succession composed of dark grey and greenish shales with sandstones, grits and thin limestones. The lower part of the succession, Lanarkian and lower Yorkian, appears to be represented.

The Armorican group extends from the Ruhr Coalfield of Germany, through the Pas-de-Calais Coalfield in the Netherlands and

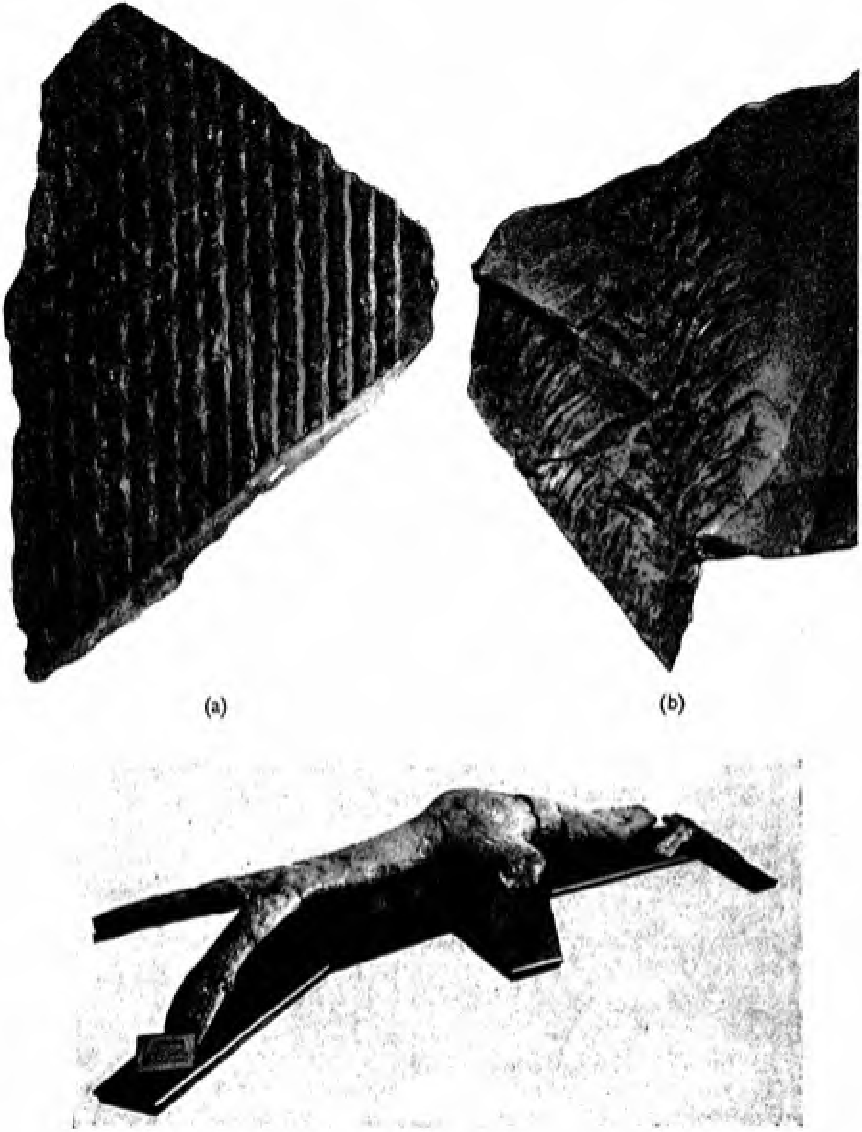


FIG. 60. FOSSIL PLANTS FROM THE COAL MEASURES (LYCOPODS)

(*a*) *Sigillaria rugosa* Brongniart; part of stem with leaf scars; Nine Feet Seam, Cymmer: *Ex G. F. Martyn Collection* (about one-third natural size). (*b*) *Lepidodendron* acutum, Prest; small stems with attached leaves; Pentre Seam, Gilfach Goch: *Ex David Davies Collection* (about one-half natural size). (*c*) Part of the root system (*Stigmaria*) of a fossil tree from above the Rock Vein, Bedwas; the specimen is about 10 feet long.

northern France, across England from Dover to Wales and on into the Munster and Leinster Coalfields of Ireland.

Folding with east-to-west axes is intense in the Ruhr and Pas-de-Calais Coalfields (Fig. 61), overfolding is common, and repetition of seams as many as five times due to folding occurs in Belgium, where Devonian and Lower Carboniferous rocks are thrust over the Liége and Namur Coalfield. By similar thrusting from the Mendips, Carboniferous Limestone has been pushed over the Radstock Coalfield.

In South Wales the "rank" of the coals increases from east to west, that is their volatile constituents decrease and the coals change in character from bituminous through steam coals to anthracites. The base of the Millstone Grit is marked by a massive sandstone known

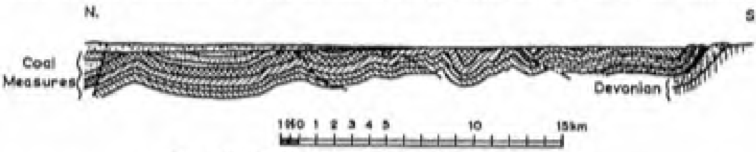


FIG. 61. STRUCTURE OF THE RUHR COALFIELD

as the Farewell Rock, and the Middle Coal Measures contain the Pennant Sandstone Series, which has its counterpart in the arenaceous development near the same horizon in the Forest of Dean and Bristol and Somerset Coalfields. In the former area the Coal Measures are Staffordian and Radstockian only. The concealed Dover Coalfield, the only true concealed coalfield in the British Isles, has the Coal Measures buried to a depth of 1,000 ft, the thickness reaching 2,800 ft in the centre thinning out towards the edges of the basin. The rocks belong to the Upper Staffordian and Radstockian divisions.

The Midland Coalfields of South Staffordshire, Warwickshire and Leicestershire, owing to their occupying part of the site of St. George's Land (Fig. 54), which was not submerged during Lower Carboniferous times, are rather unique in that the Upper Carboniferous lies directly on Pre-Carboniferous rocks. Much of the area is partly concealed by New Red Sandstone. The barren red measures of the upper division are well developed. Both the Warwickshire and the South Staffordshire Coalfields have local, thick seams, 20 and 30 ft in thickness respectively, which are produced by thinning of intermediate dirt bands between the separate layers which elsewhere increase in thickness to give five and seven distinct seams in the respective areas. An explanation of the formation of split seams will be given in a later chapter.

The Armorican Group of Coalfields

The concealed DOVER OR EAST KENT COALFIELD lying below Tertiary, Cretaceous, and Jurassic rocks (Fig. 62), on the NE. corner

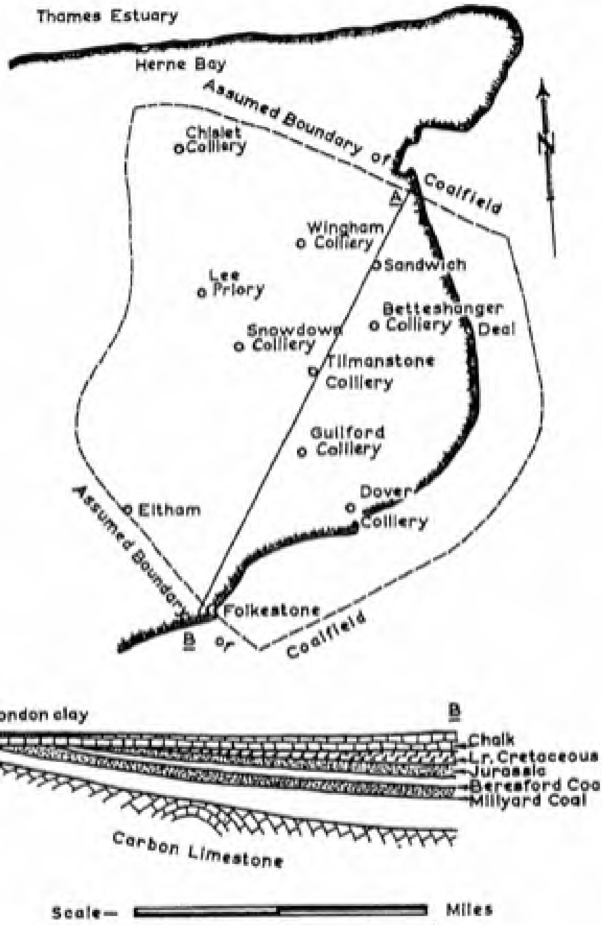


FIG. 62. THE KENT COALFIELD

of the Weald links up with the Continental Coalfields and includes an undersea extension to the east of unknown area, conservatively estimated at fifty square miles. The landward field is some 200 square miles in extent and stretches from a boundary running NW. through Ramsgate to a similar boundary through Folkestone,

though between lines running NW. through Dover and Folkestone lies an area of some fifty square miles where, although Coal Measures are present, the occurrence of commercially workable seams has not yet been proved. The coalfield extends fifteen miles inland NW. from the coast. Although conjectured in the 1850's the existence of the field was not definitely established until 1890 and it has since had a chequered career, quite a number of sinkings through the heavily watered chalk and Oolite sands being abandoned.

The coalfield lies in a deep basin with its axis running in a NW.–SE. direction, the deepest point 3,850 ft below O.D. occurring at Guildford. In addition to the Coal Measures, Jurassic ironstones, containing about 30 per cent of iron, are present over an area of sixty square miles. The seams crop out under the newer rocks in a horse-shoe concentric form with the seaward end open. The seams occur in two belts separated by up to 800 ft of relatively barren strata. The Upper, sandstone, division 2,100 ft in thickness in the centre of the basin contains six seams including, in descending order, the Beresford, the Snowdown Hard and the Betteshanger F or Millyard Seam at the bottom below which is a marine band which separates the two divisions. The Lower, shale, division is 700 ft in thickness and contains eight seams rather thicker than those of the upper division. Many of the total of fourteen seams are known only from cores obtained in boring, so that their thickness and qualities are not yet accurately known. The coals obey Hilts' Law and volatile matter content decreases with depth but all seams increase in volatile content to the north-west by as much as 17 per cent. The coals therefore rank from semi-anthracitic and coking coals to high volatile gas coals. They are generally friable but of high calorific value.

THE BRISTOL AND SOMERSET COALFIELD. The six detached areas of Coal Measures which form this coalfield form an equilateral triangular-shaped area bounded on the south by the ridge of Carboniferous Limestone and older rocks of the Mendips, the Jurassic escarpment of the Cotswolds and on the west by the Severn (Fig. 63, *bottom*). Extending from Cromball in the north to the slopes of the Mendips in the south, some twenty-six miles, and from Nailsea to Bath, a distance of twenty-four miles, the exposed coalfield covers seventy square miles but three times that area is concealed beneath practically horizontal Mesozoic rocks, of no great thickness in the coalfield area, consisting of Triassic and Jurassic strata. The Coal Measures are steeply inclined and faulted with overthrusting and inversion and are divided into separate basins. The main portion of the field consists of a complex basin with Coal Measures outcropping all round the edges on the west and south-east under newer rocks and on

the south and north-east at surface. The Kingswood Anticline running E. and W. divides the field into the northern, Coalpit Heath, area and the southern, Radstock, area, the latter with the Farmborough Fault across the middle, and in this region the full succession of Coal Measures is present. On the west of the main portion are

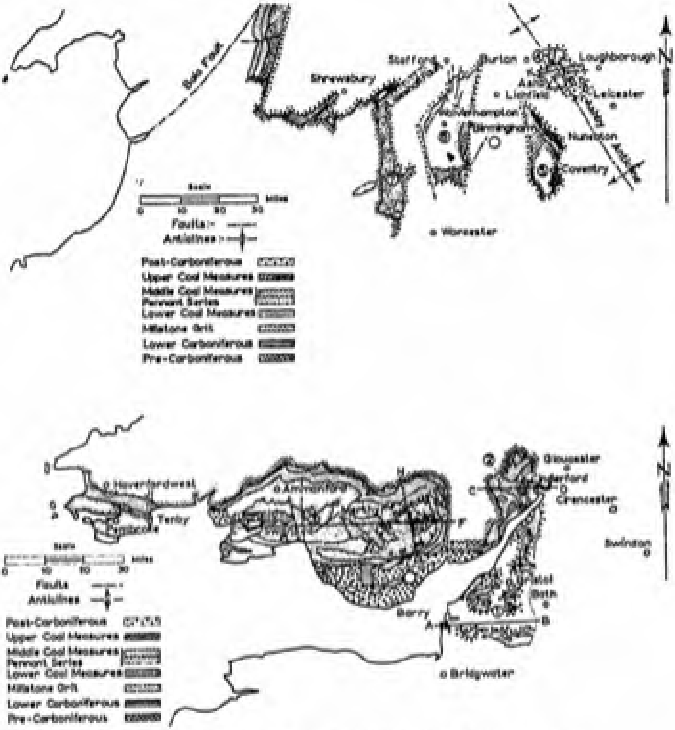


FIG. 63. MIDLAND AND ARMORICAN COALFIELDS

several detached areas the most important being the Nailsea basin consisting of a western pitching syncline, exposed to the east. Concealed extensions of the coalfield may exist north and south of the Mendips.

The Coal Measures which are productive in the Upper Coal Measures, Radstock Series, and possibly correlate with the lower part of the Stephanian of the Continent and the Keele Beds of the Midlands Coalfields, consist of two series of productive measures with a thick barren arenaceous facies between, the Pennant Series (Fig. 64).

Resting on Millstone Grit the succession consists of—

Upper Coal Series {Radstock Group 1,000 ft; Barren Red Group 500 to 700 ft; Farrington Group 700 ft}

Pennant Series—attaining a thickness of 2,000 to 2,500 ft

Lower Coal Series {New Rock Group 1,500 ft thick; Vobster Group 1,500 ft thick}

Millstone Grit

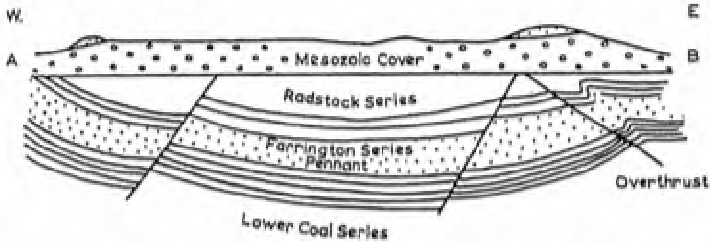


FIG. 64. SECTION OF BRISTOL COALFIELD IN DIRECTION *A–B*, FIG. 63
(¼ in. = 1 mile)

The Lower Coal Series, which contains the better seams, has eight seams in the Vobster Group and eighteen in the New Rock Group; the Pennant Group has ten seams in the Farrington Series separated by 500 ft of barren measures from six seams in the Radstock group above.

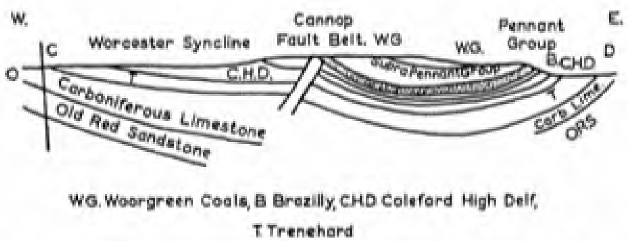


FIG. 65. SECTION OF FOREST OF DEAN COALFIELD IN DIRECTION *C–D*, FIG. 63
(¼ in. = 1 mile)
WG, Woorgreen Coals; *B*, Brazilly; *T*, Trenchard; *CHD*, Coleford High Delf.

Most of the seams are thin, often less than 24 in. in thickness, but are of good quality with carbon content between 84 and 90 per cent and volatile matter content between 40 and 22 per cent, so that many of the seams are high-rank coking coals.

THE FOREST OF DEAN COALFIELD (2, Figs. 63 and 65), often

regarded as an outlier of the South Wales Coalfield, consists of a basin of Coal Measures resting unconformably on older strata consisting of Old Red Sandstone on which lies conformably Lower Carboniferous Limestones containing brown Haematites. The field, lying in a deformed hollow in the Old Red Sandstone between the rivers Wye and Severn, extends over thirty-four square miles from Mitcheldean in the north to Lydney in the south, a distance of ten miles, with a breadth of about six miles between Coleford and Cinderford.

The coalfield is unique in its ancient mining customs in that the rights of mining "gales" from the Crown can only be granted in the first instance to all male persons born and abiding in the Hundred of St. Briavels and these rights were preserved under the Coal Act, 1938.

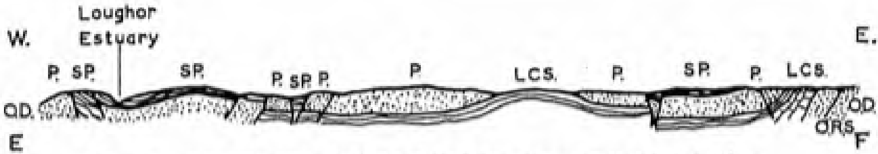
Folding inside the basin along north and south axes has produced a flat-bottomed syncline or main basin flanked on the west by the Cannop Fault Belt, downthrowing to the west, followed by the Worcester Syncline, and on the east by the Staple-Edge monocline downfolding the measures to the west by 700 ft. The Coal Measures are nearly flat in the centre of the main basin and dip 1 in 3 eastwards on the west flank and westwards on the east flank at 12 to 25 degrees. The seams occur in the Staffordian and Radstockian, that is higher in the Upper Carboniferous succession than is usual, and are divisible into three groups. The Trenchard Group at the base is 50 to 400 ft in thickness, with the Coleford High Delf Seam, generally 3 ft 6 in. to 5 ft thick, at the top and the Upper and Lower Trenchards below which unite in the south to form a single seam 4 ft 6 in. in thickness. The next group is the Pennant consisting of massive sandstones with shales and a few coals, 600 ft thick in the north increasing to 800 ft in the south, including above the main seam, the Coleford High Delf, the Whittington, Yorkley, and the Brazilly at the top.

The top or Supra-Pennant Group, consisting of shales, sandstones, and coals, may be subdivided into a lower productive division 300 ft in thickness with eight workable seams and an upper division 800 ft in thickness of which sandstones and thin coals including the Woorgreen coals at the top, each 2 ft thick, which are present only in the centre of the main basin.

The seams in this coalfield are liable to splitting and washouts occur in the Pennant and Trenchard groups but not in the Supra-Pennant group. Strict correlation with similarly-named groups of strata in the South Wales Coalfield does not obtain. The principal seam worked is the Coleford High Delf which varies in character

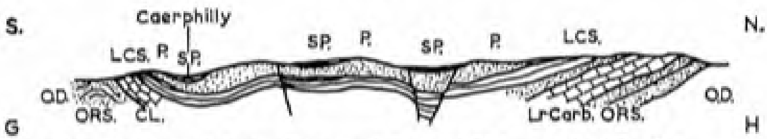
from a medium coking gas coal in the deeper central portion of the field to a free-burning coal on the margins.

THE SOUTH WALES COALFIELD (3, Figs. 63, 66, 67 and 68), by far the largest and most important of the Armorican group, like the others occupies a synclinal fold, with an east to west axis, sunk in Old Red Sandstone and Lower Carboniferous strata (Millstone Grit



S.P. Supra-Pennant Series, P. Pennant Series, L.C.S. Lower Coal Series.

FIG. 66. SECTION OF SOUTH WALES COALFIELD IN DIRECTION *E–F*, FIG. 63
(¼ in. = 6 mile)



S.P. Supra-Pennant Series, P. Pennant Series, L.C.S. Lower Coal Series,
C.L. Carbon Limestone, O.R.S. Old Red Sandstone.

FIG. 67. SECTION OF SOUTH WALES COALFIELD IN DIRECTION *G–H*, FIG. 63
(¼ in. = 3 miles)

FIG. 68. SECTION OF PEMBROKESHIRE COALFIELD IN DIRECTION *I–J*, FIG. 63
O, Overthrust. (¼ in. = 1 mile)

and Limestones) which form the boundaries of the completely exposed field except on the seaward side where deep bays cut into it at Swansea and Carmarthen. It extends from Pontypool westwards to St. Bride's Bay, a distance of ninety miles and has an average width of fifteen miles and a maximum of eighteen miles in Glamorganshire. The Lower Coal Measures are but poorly represented but workable seams occur in the Upper Coal Measures, Supra-Pennant Series, above the upper portion of the Middle Coal Measures represented by the Pennant group which in the eastern part of the

field is barren of workable seams, but with important coals in the upper portion in the west.

The area covered, some 800 square miles, consists of a high plateau more than 1,000 ft above O.D. intersected by steepsided valleys from which access is obtained to the deeper coals beneath the Pennant Sandstone forming the plateau. The field is fringed on its northern and southern margins by moorland of Pre-Coal Measure Age and there is a coastal strip of flat country. Carmarthen Bay divides the field into two portions, the main portion to the east and the smaller Pembrokeshire field to the west, the latter being much narrower, about four miles.

In the main basin the Lower Coal Series outcrops on the north and south, the latter in a narrower strip in which the measures dip steeply to the north. On the north and in the centre the dip is more moderate and mining conditions are consequently easier.

Subsidiary folds run east and west along the main basin sometimes replaced by faulting, as in the Moel Gilau Fault downthrowing south a maximum of 700 yd in the southern portion. A series of normal faults generally downthrowing to the west, cross the field running NNE.–SSW. and gradually introduce higher measures so that the lower coals are depressed to a depth of 4,000 ft and more in the Swansea area. A second series running WSW.–ENE. commences with the Vale of Neath disturbance and increases in intensity to the west where overthrusting occurs.

The succession of strata above the Millstone Grit or Farewell Rock consists of the Lower Coal Series, often subdivided into Lower, White Ash, Series and Upper, Red Ash, Series, followed by the Pennant, arenaceous, Series with the Supra-Pennant (Upper Coal Measures) Series at the top, the whole of the succession increasing greatly in thickness from east to west. Most of the output of the field comes from the lower portion of the Lower Coal Series. This series increases from 750 ft in thickness in the east to 3,000 ft at Llanelly, sandstones in particular increasing in thickness. The Rhondda No. 2 seam, also named the Tillery and the Ynisarwed, marks the summit of the series of which the most important portion is the lower containing some twelve seams below and including the Two Feet Nine Seam. Splitting and faulting makes correlation of seams difficult but the Nine Feet or Rhas Las of North and East Glamorgan appears to correspond with the Black Vein of Monmouthshire and the Stanllyd and Big Vein of the West. The Upper portion of the Lower Coal Series is barren in the eastern district but in Glamorganshire six seams occur including the No. 2 Rhondda at the top. The Pennant Series consists mainly of coarse grits without

workable seams in the east about 630 ft in thickness increasing to 2,700 ft in the west, the thickening being accompanied by the development of shales and some half dozen workable coals in the upper portion.

Much of the Supra-Pennant Series has been denuded but patches occur varying in thickness from 300 to 1,000 ft above the Mynyddislwyn or Swansea Four Feet at the base, correlating with the Llantwit No. 3 Vein of the Rhondda Valley, which contains workable seams.

The remaining portion of the coalfield, in Pembrokeshire, is complicated by intense faulting and overthrusting to such an extent

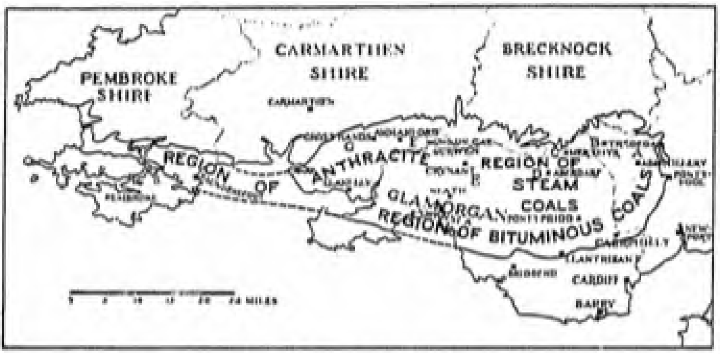


FIG. 69. MAP ILLUSTRATING THE CHANGE IN RANK OF SOUTH WALES COALS

that Pre-Cambrian and Silurian strata have been carried over the Coal Measures. The thrust came from the south in a northerly direction and the anthracites have been shattered to small coal or "culm." Squeezing out of the middle limb of folds and local thickening, through the closing of a synclinal fold, produces what is known as a "slatch."

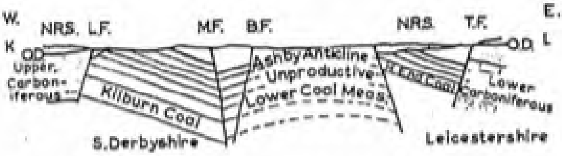
The coals, which are all anthracites, belong to the lower half of the Lower Coal Series which increases in thickness from east to west and the number of seams, mostly thin and less than 2 ft in thickness, increases in the same direction to some twenty-two.

Rank of South Wales' Coals

Variation of rank in coals is best illustrated in this coalfield. The lowest rank coals are those in a narrow belt along the eastern and southern crops which are bituminous gas coals with volatile matter content of 35 per cent or above, the highest rank anthracites in the NW. corner of the main coalfield and in Pembrokeshire in which the

volatile matter content is only 4½ per cent. The rate of change of rank may be determined by plotting the isovols, lines joining points of equal volatile-matter content. The rate of increase of rank is gradual, but differs in different parts of the field, being obviously affected by the intensity of tectonic action in the vicinity. Thus increase of rank in a few miles north of the Gower Peninsula is the same as that which occurs in 50 miles from east to north-west. Rank also changes with position in the vertical succession, highest rank at the bottom, but the vertical range at any point is considerably less than the lateral range across the coalfield.

The range of carbon content from east to west is from 84 to 94½



NRS. New Red Sandstone. LF. Linton Fault. MF. MF. Moira Fault
BF. Boothorpe Fault. TF. Thringstone Fault.

FIG. 70. SECTION OF SOUTH DERBYSHIRE AND LEICESTERSHIRE COALFIELD IN DIRECTION *K–L*, FIG. 63
(Horizontal scale: ¼ in. = 2 miles. Vertical scale: ¼ in. = 2,000 ft.)

per cent and the corresponding types of coal which result from change in rank are shown in Fig. 69.

The Midland Group of Coalfields

These coalfields fringe the central geosyncline of Coal Measure times with its centre at Buxton and, occupying the site of St. George's Land of Lower Carboniferous times, the Middle Coal Measures rest upon basins in the Pre-Carboniferous rocks arranged radially like the spokes of a wheel round the geosyncline centre (Fig. 54). The rate of depression was as much as five times as great at the hub as at the periphery so that the deeper coals of the centre, in the coalfields of Yorkshire, North Derbyshire, Lancashire, and North Staffordshire, are high rank coking coals while in the peripheral fields of the Midland Group they are free-burning and grade down to sub-bituminous.

THE LEICESTER AND THE SOUTH DERBYSHIRE COALFIELDS (4, Figs. 63 and 70), lie on each side of an anticline through Ashby-de-la-Zouch pitching in a south-easterly direction, the fields lying in an ancient pocket between the Cambrian rocks of Warwickshire and

the Pre-Cambrian of Charnwood. Each is eight miles in length and four miles in width and contains about 1,500 ft in South Derbyshire and 700 ft in Leicestershire of Middle Coal Measures with unproductive Lower Coal Measures exposed in the anticline between the fields.

The boundary of the Leicestershire Coalfield on the east is the Thringstone fault, bringing older rocks to the surface. In the west the Productive Measures outcrop on the side of the anticline. To the north the seams outcrop and to the south they again outcrop but under the New Red Sandstone.

The boundary of the South Derbyshire field to the north is by turn-up of the seams to outcrop under the New Red Sandstone, on the west the boundary is indefinite but faulting is indicated, while on

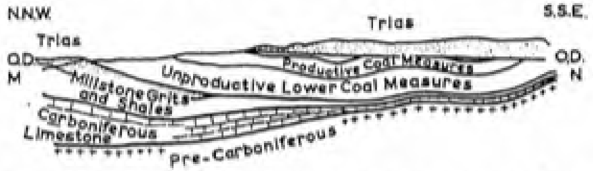


FIG. 71. SECTION OF SOUTH DERBYSHIRE AND LEICESTERSHIRE COALFIELD
($\frac{1}{2}$ in. = 3 miles)
Showing thinning of carboniferous strata to the south against ancient land-mass.

the east the Boothorpe Fault throws down to the west about 1,000 ft. To the south and west the boundaries are at present indeterminate. Upper Coal Measures are present in the Church Gresley area.

In South Derbyshire the Kilburn Coal, 4–5 ft in thickness, lies at the base of the Middle Coal Measures and the main seams exploited are the Eureka, 4–5 ft thick, the Stockings, 5–8 ft, the Woodfield, also 5–8 ft, the Main Coal, 12–16 ft, the Dickey Gobbler, 3–4 ft and the Ell Coal, 4–9 ft in thickness.

In the Leicestershire Coalfield the Middle Coal Measures are only about one half the thickness of those of South Derbyshire. The Heath End Coal lies at the base, above which are the Roaster Coal, 2–4 ft, the Lount Coals, the Main Coal, 5–7 ft, the Yard, 2–5 ft and the Slate Coal, 4–9 ft in thickness.

An interesting account of boring to determine the southern limit of the field is contained in the *Transactions of the Institution of Mining Engineers*, Vol. 104, p. 703 in a paper entitled "Driving of two drifts by the Desford Coal Co., Ltd., at Merry Lees" by Butterley and Mitchell. The thinning of the limestone and the Millstone Grit towards the Charnwood Forest is a feature of this coalfield (Fig. 71).

The coals of this field are free-burning, non-caking or very weakly caking of relatively low rank.

THE WARWICKSHIRE COALFIELD (5, Fig. 63), is separated from that of Leicestershire by an anticline of Cambrian and Pre-Cambrian rocks which are exposed and against which the Coal Measures rise sharply. On the west it is separated from the South Staffordshire Coalfield by a ridge of Cambrian rocks which outcrop at Dost Hill.

The coalfield consists of an open syncline with a north to south axis twenty-four miles in length from Tamworth to Binley widening from two to seven miles at Nuneaton as it pitches to the south. Upper Coal Measures, attaining a thickness of 4,000 ft between Kenilworth and Coventry, occupy most of the area of 150 square miles and are unproductive except for unworkable thin coals.

The Carboniferous Limestone, Millstone Grit and Lower Coal Measures are absent, the Productive Middle Coal Measures, exposed as a narrow fringe on the east and north, 850 ft in thickness in the north and thinning to 450 ft in the south at Coventry, rest unconformably on Cambrian Shales. The Cambrian is traversed by numerous igneous dykes and sills but these do not affect the Coal Measures.

On the east and west are the Boundary Faults towards which the measures rise steeply, but except for small faults, the coalfield is not disturbed except by washouts in the Two Yard and the Thick Coal. Some fourteen seams of coal of good thickness are worked between the Bench, 2 ft 6 in. to 11 ft 6 in. in thickness at the base, and the Four Feet, 2 ft 1 in. to 4 ft 10 in. thick, at the top. From Stockingford to the south and west the Slate Coal, 6 ft 4 in., the Ell, 3 ft 3 in., the Ryder 5 ft 5 in., the Bare, 2 ft, and the Two Yard at the top, 6 ft, separated only by narrow dirt partings unite to give the composite Thick Coal or Hawkesbury Seam from 18 to 24 ft in thickness.

The eastern limit of the coalfield under the New Red Sandstone, east of the Eastern Boundary fault, is not known and the Coal Measures may be absent or present only in small pockets, while elsewhere the Trias rests on Pre-Coal Measures rocks. On the west the Coal Measures will be deep, if present, west of the Western Boundary Fault. To the south reserves should be large in the Coventry area but water may be expected in sinkings from the sandstones of the Upper Coal Measures and cementation methods will probably be required as at Coventry Colliery. The coals of this field are also very weakly or non-caking and have a high reputation as free-burning house coals.

THE SOUTH STAFFORDSHIRE COALFIELD (6, Fig. 63), is a flat-topped ridge or plateau of Carboniferous rocks, twenty miles in length, with a north and south axis and from four to eight miles in width, tilted

towards the south and rippled by minor folds impressed posthumously on older folding. On the east, separated from the coalfield by the Eastern Boundary Fault downthrowing to the east and bringing Upper Coal Measures and Trias opposite the Middle Coal Measures, is a steep-sided syncline in the Trias several thousand feet in depth. On the west also a Boundary Fault brings red Upper Coal Measures and Trias opposite the Coal Measures. The coalfield extends under the Trias cover both east and west of the Boundary Faults but the extent of these concealed fields is as yet indeterminate.

Thin beds of Carboniferous Limestone and Millstone Grit have been found by boring to the north of the coalfield but this elsewhere lies on a floor of Silurian rocks which an anticline at Dudley and Sedgley, running NW.–SE., brings to the surface and igneous intrusions occur along the same line.

The coalfield is divided into two portions by the Bentley Faults running east and west through Walsall, the northern portion being known as the Cannock Chase Coalfield.

In this portion of the field the Coal Measures dip to the west and this is accentuated by faults downthrowing to the west. The Middle Coal Measures attain a thickness of 2,000 ft in the north and contain fourteen seams, mostly exceeding 5 ft in thickness. Near the bottom the Deep, Shallow, Cinder and Bass seams often occur in close proximity.

In the southern portion the Middle Coal Measures are thinner increasing from 600 ft in the south in a northerly direction. Snags of Silurian rock rise through the Coal Measures. Eight seams have been worked, including the Thick Coal from 18 to 30 ft in thickness, but this portion of the exposed field has been largely exhausted and has become waterlogged but working continues in the concealed areas to the east and west.

The Upper Coal Measures, similar in character to those of North Staffordshire and Warwickshire and barren of coal, outcrop along the western boundary and in the centre of the exposed Cannock Chase portion of the field. Upper Coal Measures are also exposed on the eastern, western and southern margins in the southern portion of the coalfield, faulted in by Boundary faults, but are conformable with the Middle Coal Measures. In all some 3,500 ft of red Upper Coal Measures are present.

The coals are again of the high volatile type, weakly or non-caking.

THE FOREST OF WYRE COALFIELD (9, Fig. 63), is a further example of a patch of Coal Measures filling up a hollow in the eroded surface of Pre-Carboniferous rocks. It extends south of Bridgnorth, down

the Severn Valley and occupies some fifty square miles. The northern boundary consists of an anticline where the Upper Coal Measures, which are continuous into the neighbouring coalfield of Coalbrookdale, rest directly upon Pre-Carboniferous rocks. On the west and south outcrops of Old Red Sandstone strata terminates the Coal Measures, but on the east, towards which the Coal Measures are inclined, the measures pass beneath barren Upper Coal Measures. The coals in the Productive Measures are divided into two groups, an upper Sulphur or Highley series containing four relatively thin seams, including the Main Coal 5 ft in thickness and the Hard Coal, and a lower Sweet or Kinlet series with four seams namely, in ascending order, the Two Feet Coal 1 ft 5 in. to 3 ft, the Four-foot Coal 1 ft 6 in. to 4 ft 6 in., the Half Yard Coal 1 ft 8 in. and the Brooch Coal 4 ft to 6 ft 3 in. thick. These deteriorate to the south. Dykes and sills of olivine dolerite traverse the Coal Measures.

A small patch of Coal Measures, four square miles in extent with three seams, occurs in the Clee Hills, but the area is traversed by igneous rocks and the seams are variable in thickness. The coals of the Shropshire fields are of the weakly caking type.

THE COALBROOKDALE COALFIELD (7, Fig. 63) lies immediately north of the Forest of Wyre field and extends from Lilleshall in the north-east to Broseley in the south-west, a distance of twelve miles, and covers an area of eighteen square miles.

The Productive Measures are in the Middle Coal Measures and these, dipping eastwards, rest unconformably on Lower Carboniferous, Old Red Sandstone and Silurian rocks. They were faulted and folded posthumously along the lines of the late Silurian disturbances, with axes running NE.–SW., before the Upper Coal Measures were deposited and these rest unconformably on the eroded folds of anticlines from which certain seams have been denuded. This unconformity is known as the Symon Fault. The principal faults run in the same direction, NE.–SW., and the Lightmoor Fault, downthrowing to the east, bisects the coalfield, which is shallow to the west and deeper to the east of it. To the south the Limestone Fault follows the axes of one of the anticlinal folds.

The Lilleshall Fault bounds the coalfield on the north-west, and north-west of this fault the Keele Beds of the Upper Coal Measures rest directly on Pre-Cambrian rocks. To the east a full series of workable seams has been proved under Upper Coal Measures towards the Cannock Chase Coalfield. On the south and west the coalfield is bounded by outcrops of older rocks.

The Middle Coal Measures contain ten workable seams with the Little Flint Coal, 1 ft 6 in.–3 ft 3 in. in thickness, at the base and the

Fungus Coal, 3 ft–3 ft 4 in. at the top, including the Best or Randle and the Clod Coals 6 ft–16 ft 6 in. in thickness near the bottom.

To the west of the Coalbrookdale field near Shrewsbury, three patches of Upper Coal Measures resting on Pre-Carboniferous rocks and containing three thin seams have been worked but the Middle Coal Measures are absent.

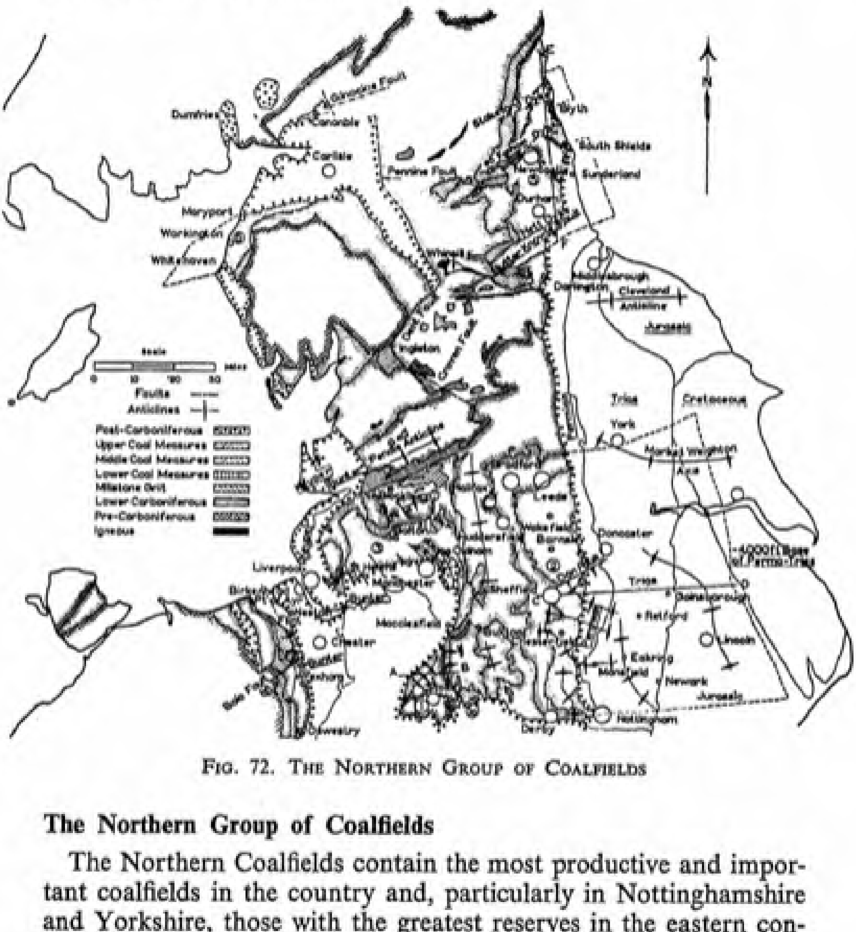


FIG. 72. THE NORTHERN GROUP OF COALFIELDS

The Northern Group of Coalfields

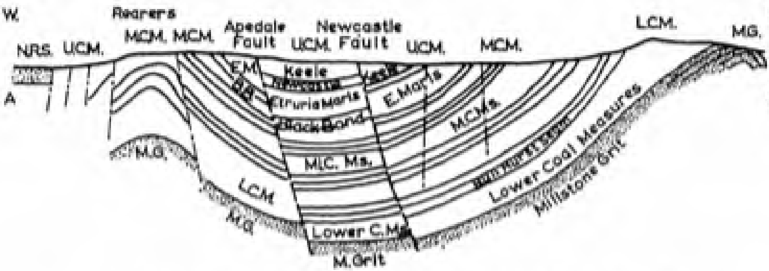
The Northern Coalfields contain the most productive and important coalfields in the country and, particularly in Nottinghamshire and Yorkshire, those with the greatest reserves in the eastern concealed portion of the coalfield under New Red Sandstone. Boring operations have also revealed the probable existence of a deep coalfield in Lincolnshire.

THE NORTH STAFFORDSHIRE COALFIELD (1, Figs. 72 and 73), occupying a triangular-shaped area some 100 square miles in extent

round Stoke-on-Trent contains the most complete development of the Upper Coal Measures characterized by their red colour and heralding the continental conditions of the next system, that of the Permo-Triassic or New Red Sandstone.

The Upper Coal Measures are divisible into four subdivisions namely in descending order—

Keele series 700 ft in thickness
Newcastle-under-Lyme series 300–600 ft in thickness
The Etruria Marls 800–1,250 ft in thickness
The Black Band series 300–450 ft in thickness.



NRS. New Red Sandstone, UCM. Upper Coal Measures, M.C.M. Middle Coal Measures, L.C.M. Lower Coal Measures, M.G. Millstone Grit

FIG. 73. SECTION OF NORTH STAFFORDSHIRE COALFIELD IN DIRECTION *A–B*, FIG. 72
(Horizontal scale: ½ in. = 1 mile. Vertical scale: ½ in. = 1,000 ft.)

The Black Band series includes a few thin coal seams and consists of shales, grits and marls, generally grey in colour, together with beds of clay ironstone, among the few iron deposits of this type still worked in this country.

The Etruria Marls are fine red and purple mottled marls and clays used in bricks, tiles and the coarser sanitary ware of the ceramic industry for which the area is justly famous, with thin bands of greenish grit, known as "espleys," approaching conglomerates in the coarser bands. Thin Spirorbis (spirally coiled, calcareous worm tube) limestones which are indicative of lagoonal conditions also occur.

The Newcastle or Halesowen series consists mainly of thick sandstones, shales and marls, grey in colour, with a few unimportant thin coals. The top group, the Keele beds, are red and purple sandstones, bright red marls and shales with thin bands of Spirorbis limestones, which frequently contain a high percentage of magnesia

usually associated with saturated saline solutions in a land-locked sea which is drying up.

The Middle and Lower divisions of the Coal Measures in this area are a normal, rhythmic alternation of shales, sandstones, fireclays and coal seams, but owing to folding the dip of the seams in the western part of the coalfield are high giving the so-called "Rearer" seams with inclinations between 45° and the vertical and in places even reversed. The Lower Coal Measures, which attain 400 yd in thickness, are steeply inclined on the east and north with the Crabtree Coal at the base which correlates with the Bullion Coal of the Mountain Mines of Lancashire and the Alton or Halifax Hard Seam of the East Midland Coalfield.

The main portion of the coalfield consists of a syncline running NNE.–SSW. pitching to the south with the Rearers anticline lying west of this main fold. Faulting is heavy, the faults being in two groups running N.–S. and E.–W. and there is evidence in the variation of the thickness of sediment between individual seams, amounting to a total of 1,000 ft in a distance of two miles, that differential movement was occurring during the deposition of the Coal Measures in this region, the variation occurring in the beds of thick sandstone in lenses, increasing in thickness in the syncline.

On the west, faults throw the New Red Sandstone opposite the Coal Measures; on the east an anticline brings Millstone Grit to the surface and trending NNW. accounts, with the Rearers anticline running NNE., for the triangular shape of the coalfield. To the south the Coal Measures dip under unconformable New Red Sandstone.

The coalfield is extremely rich, the thickness of coal seams per unit of depth is higher than in other fields. Thirty seams are present of which some twenty-three are extensively worked, mostly in the Middle Coal Measures which are from 2,500–3,500 ft in thickness. The main seams in ascending order are—

The Bullhurst, 3–15 ft thick, the Cockshead or Eight Feet Bambury, 6–10 ft, the Seven Feet Bambury, 3–7 ft, the Bowling Alley Coal, 2½–5 ft, the Rough Seven Feet, 3½–8 ft, the Great Row Coal, 5–11 ft, and the Bassey Mine, 2–4 ft at the top in the Upper Coal Measures. Many of the lower seams are high rank coking coals. When of lower rank they are liable to spontaneous combustion.

To the east of the main coalfield a series of folds produces small, detached coalfields at Shallalong, Goldsitch, Moss and Cheadle. The last is the only one of economic importance being circular in shape (*1a* Fig. 72), and occupying an area of ten square miles. It consists of an asymmetrical basin steeper on the west, faulted by two

series of faults running N.–S. and E.–W. The seams are thinner than those in North Staffordshire and, with the Crabtree Coal at the base, 2 ft in thickness, there are fourteen seams above from 1 ft 6 in. to 6 ft in thickness with the Two Yard Coal, 5½ ft thick, at the top.

THE EAST MIDLAND COALFIELD. The coal swamp area in which the coalfields were initiated covered an enormous area probably extending from the Donetz basin in Russia across Europe and the North Sea, the North and Midlands of Great Britain, Wales, across the Irish Sea to Ireland, and perhaps beyond, not necessarily as one huge swamp; but similar conditions were present simultaneously in the entire area as proved by fossil evidence.

The present position of the coalfields as isolated groups is the result of denudation and folding. The ridge or anticline on the line Stone, Castle Donnington and Ruddington divides the northern group from the Midland group; a second ridge, from Pendle Hill in Lancashire along the Wharfe Valley, separates the Nottinghamshire, Derby and Yorkshire Coalfield from that of Durham and Northumberland, while the Pennine anticline separates the Lancashire from the Yorkshire Coalfield and the Cumberland from the Durham and Northumberland Coalfield.

The Nottinghamshire, Derby and Yorkshire Coalfield (2, Fig. 72), is still one composite whole extending from Leeds in the north to Nottingham in the south, a distance of some seventy miles, with a width to the undefined eastern boundary of the concealed field, somewhere in the region of the Trent, from the outcrop of the top of the Millstone Grit, just west of Sheffield, of some forty miles, an area, therefore, of 2,000 to 2,400 square miles.

The Coal Measures attain a thickness of 5,000 ft with thirty-four workable seams of coal between the Halifax Soft and Halifax Hard, Ganister or Alton Mine at the base to the Shafton at the top, the main seams being in ascending order—The Better Bed of West Yorkshire or Kilburn of Nottinghamshire and Derby, Blocking, Silkstone or Blackshale of Nottinghamshire and Derby, Parkgate or Deep Hard of Nottinghamshire and Derby, Swallowwood or Haigh Moor of South and West Yorkshire respectively, Warrenhouse, Barnsley or Top Hard of West Yorkshire, South Yorkshire, and Nottinghamshire respectively and High Hazles or Kents Thick. The coalfield is exposed on its western edge for a width of twenty-two miles but the exposure narrows to the south.

Eastwards the coalfield becomes concealed under an unconformable cover of Permo-Triassic rocks and, in the south, Jurassic rocks, which dip to the east and reach a thickness of 4,000 ft in the region of Lincoln.

The stratigraphical succession is as follows, in descending order—

Glacial and Drift deposits of clays, sands and gravels	0 to 170 ft
Jurassic clays, limestones and sands	over 1,400 ft
New Red Sandstone marls and sandstones . .	up to 2,000 ft
Permian limestones, marls and basal breccia . .	0 to 700 ft
Upper Coal Measures of red, purple, brown, grey and green sands and mudstones representing Etruria Marls Newcastle and Keele Beds with thin unworkable coals	up to 600 ft
Middle Coal Measures with Silkstone Coal at base and red sandstone, with pigment leached from ironstone bands, near the top	2,000 to 3,000 ft
Lower Coal Measures with many coals, some of the sandstones becoming coarse in texture and similar to Millstone Grit	1,000 to 1,650 ft

The Middle and Lower Coal Measures thin both southwards and eastwards from their maximum development in the latitude of Sheffield where the coal seams amount to rather less than five per cent of the Coal Measures.

The most productive zone is the 2,600 ft between the Beeston and Shafton Coals in South Yorkshire and the 2,000 ft between the Blackshale and High Main Coals in Nottinghamshire and Derbyshire. The Warrenhouse-Barnsley-Top Hard is the predominant seam extending over an area of 600 square miles, although it varies in thickness, quality and rank. It averages 5 ft in thickness but reaches 10 to 11 ft in the east. The characteristic "hards" band of dull durain, from 1 to 4 ft in thickness, occurs near the top of the seam proper and the increase in thickness is generally due to the thickening of the Top Softs and coal bands above the seam proper (Fig. 74.) These, between Woolley and Askern, split from the true Barnsley, which dies out, and continue into West Yorkshire as the Warrenhouse Coal and the Gawthorpe Seam.

To the east of the exposed coalfield the newer collieries have proved the eastward attenuation of the Coal Measures with failure of intermediate seams between the major and constant seams and also a reduction of the rank of the coals east of a line through Frickley and Bullcroft.

The Barnsley and the seams above are free burning, those below and the Barnsley Brights in the deeper sub-basins grade into gas coal and coking coal and are of higher rank.

Several marine bands occur and are invaluable for correlation. The most important, the Mansfield Marine Band, occurs at distances

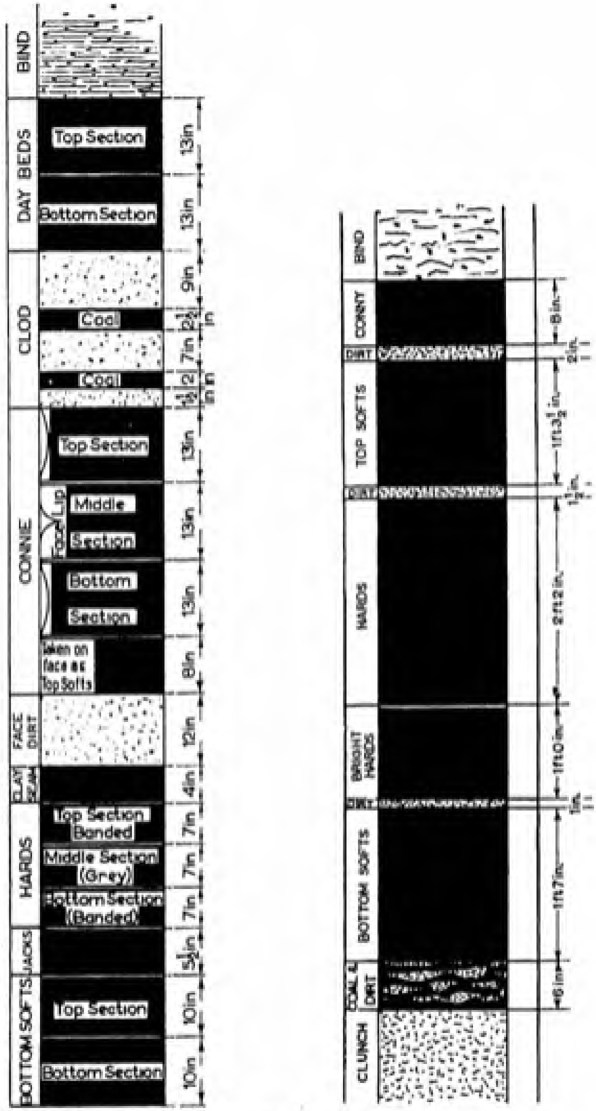


FIG. 74. SECTIONS OF THE BARNSLEY SEAM

varying from 430 to 750 ft above the Barnsley seam depending on the rate of deposition of strata in the particular location involved.

In shape the coalfield is that of an oval basin with the major axis running north and south, relatively shallow, with a number of shallow anticlines explored on the west by colliery workings and revealed by geophysical prospecting in connection with the successful search for oil occurring in the tops of the anticlines in the Millstone Grit of the Eakering district.

The main folds are shown in Fig. 72 and cross-section Fig. 75. The faulting is the normal arrangement of two sets at right angles,

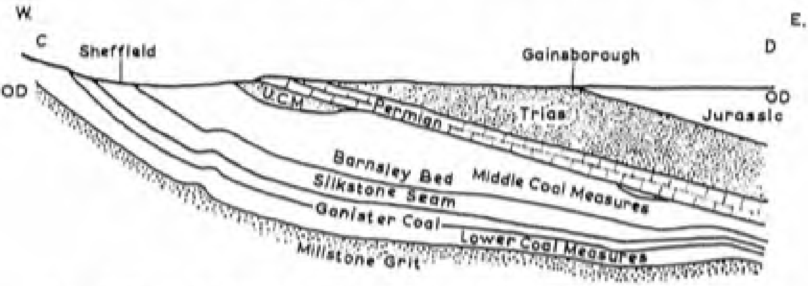


FIG. 75. SECTION OF THE YORKSHIRE COALFIELD IN DIRECTION *C–D*, FIG. 72
(Horizontal scale: $\frac{1}{4}$ in. = 6 miles. Vertical scale: $\frac{1}{4}$ in. = 3,000 ft.)

dip and strike, with the Don Faults and accompanying monocline causing north-eastward shift of the outcrops in the region of Rotherham.

The faulting and folding in the Coal Measures is not repeated in the Mesozoic rocks above so that structures in the latter are no guide to conditions in the Coal Measures below. A small number of faults are posthumously repeated in the Permo-Trias with diminished throw.

As already indicated the coals of West Yorkshire are strongly and medium caking, those of South Yorkshire vary from strongly to weakly caking and those of Derbyshire and Nottinghamshire are very weakly caking.

THE LANCASHIRE AND CHESHIRE COALFIELD (3, Fig. 72), with the neighbouring sister coalfields of North Wales, is the western counterpart of the East Midland Coalfield and the succession is similar though the Coal Measures are much more faulted and more steeply inclined. The Lower Coal Measures occupy hilly sites and from these positions has been derived the name of the most important seams in them, the Mountain Mines, while the Middle Coal Measures occupy the lower ground and are extensively overlain by glacial drift,

from the Irish Sea Ice-sheet, which may attain a thickness of over 200 ft.

The exposed coalfield is triangular in shape with the apex to the north-east, occupies an area of some 220 square miles, and in the area the Carboniferous system attains a total development of 11,000 ft.

The coalfield is bounded on the north and east by Millstone Grit and on the west and south by the newer rocks of the Permian and particularly the Trias. In the St. Helens area the Carboniferous is succeeded directly by the lower divisions of the Triassic Bunter Sandstone. The extension of the coalfield under the Cheshire basin is indeterminate but will be under a great thickness of Trias, while on the west borings at Croxteth and Formby, near Liverpool, indicate that the Coal Measures may outcrop under the newer rocks or, alternatively, be at a depth greater than the 4,500 ft generally assumed to be the limit of economic coal-mining at present but not necessarily in the future.

The rocks exposed on the coalfield may be tabulated as follows—

Trias	Keuper Marls and Sandstones	4,200 ft
	Bunter Sandstone	3,000 ft
Permian	Manchester Marls	400 ft
	Collyhurst Sandstone	2,400 ft
Upper Coal Measures	Purple, red and grey marls including Heaton Park and Ardwick Series—but no workable coals	700–1,200 ft
Middle Coal Measures	With Worsley Four-feet at Top and Arley or Little Delph Seam at base and containing the main seams	3,000 ft
Lower Coal Measures	With Mountain Mines containing distinctive ferruginous "coal balls"	1,600 ft

There are unconformities between the Permo-Trias and the Upper Coal Measures and between the Upper and Middle Coal Measures.

The coal seams are known by a wide variety of local names which, together with the faulting, makes correlation difficult. The main seams however starting at the base of the Middle Coal Measures with the Arley or Little Delph (St. Helens area) are the Smith or Rushey Park, the Haigh Yard, the Ravine or Plodder, the Trencherbone, the Wigan or Ravenhead Mines, the Pemberton or Florida Mines, the Ince Mines or Crumbouke and at the top the Worsley Four-Feet or Parker Mine.

The inclination is south near the Rossendale anticline, separating

the Burnley syncline from the Manchester and South Lancashire areas, and west in the remainder of the field except where local folding influences the inclination.

Faults of large throw, often over 500 yd, running NW.–SE. divide the coalfield into a number of parallel strips with a second set running east and west. The Rossendale anticline runs in the latter direction and brings Millstone Grit to the surface as a ridge which almost completely separates the Burnley-Blackburn Syncline, in which coals of the Lower Coal Measures predominate, from the remainder of the coalfield. The majority of the faulting occurred before the Permian was deposited but some posthumous faulting has taken place.

It will have been remarked that in both this coalfield and that on the other side of the Pennine anticline, the East Midland Coalfield, the future reserves of coal depend to a large extent upon the relation between the Coal Measures and the newer rocks above them and their inclinations relative to each other in the unexplored concealed areas. It is obvious that if the Coal Measures outcrop beneath these newer rocks hopes of increased reserves in deep concealed fields will not be realized.

The majority of the Lancashire coals are free burning, but those which were originally buried deepest are coking coals of higher rank—the Mountain Mines and lower seams of the Middle Coal Measures of South Lancashire. The types of coal in this field range from coking coals with a volatile matter content below 30 per cent to high volatile, very weakly caking coals.

The Lancastrian or Millstone Grit is exceptionally thick north of the Lancashire coalfield where more than 1,500 yd of shales and grits were deposited decreasing in thickness to the south. The steep dips of this coalfield in the south-east corner are partly compensated by throw-back faults.

North Wales Coalfields

This group of coalfields (4, Fig. 72), extends over a length of forty-five miles on the western margin of the Cheshire basin occupied by a great thickness of Keuper (Triassic) rocks. The connection with the Lancashire Coalfield is through the Wirral Peninsula at Neston where the Coal Measures outcrop under Boulder Clay. As the inclination of the coal measures in North Wales is to the east or north-east and the dip of the Coal Measures of the extreme south-west corner of the Lancashire Coalfield, at Cronton Colliery on the opposite side of the Mersey, is one in four-and-a-half to the SW., it is evident that if the connection is continuous and unaffected by heavy faulting a deep trough must exist under the Mersey.

At Neston four seams occur and the topmost, the Six Feet, has been correlated tentatively with the Rushey Park Seam of Lancashire.

The two main portions of the coalfield, the Flintshire and the Denbighshire fields, are divided by the Great Bala Fault. The Carboniferous succession is very complete, up to 9,500 ft being represented, and the Upper Coal Measures are particularly well developed. The Carboniferous rests upon intensely folded Ordovician and Silurian rocks.

In Denbighshire the Upper Coal Measures reach their maximum development and consist of—

The Erbistock Beds of purple, red and variegated sandstones and marls with a few thin coals and limestones .	3,000 ft
The Coed-yr-alt Beds of greenish sandstones and red and green marls with thin limestones	500 ft
Ruabon Marls of purple, red and green marls with four coals including the Morlais Main Coal 4 ft 9 in. thick .	1,100 ft

The two lower divisions are absent in the Flintshire Coalfield.

The Middle Coal Measures are some 2,000 ft thick in Denbighshire with thirty seams and 1,250 ft in Flint with thirteen seams where, in the area in the neighbourhood of Flint, a portion of the Productive Coal Measures, including the most important seam, the Main Coal, is replaced by red measures without coals, similar to those of the Upper Coal Measures.

In the Ruabon area a series of fireclays, siliceous clunches and marls, 100 ft in thickness outcrop and are known as the Buckley fireclays. They form the basis of a flourishing refractory brick industry. The Yard Seam of Flintshire is an important House Coal and a Cannel Coal occurs at Leeswood 250 ft below the most important coal in both fields, the Main Coal, 10 ft 6 in. in thickness.

The Lower Coal Measures are unproductive and attain their maximum thickness of 1,000 ft in Flintshire. They consist of the Hollywell Shales with earthy limestones and are absent in the Ruabon-Chirk area.

The folding and faulting determines the shape of the separate fields. The Flintshire Coalfield lies in a syncline to the west of the Horse-shoe Anticline which may continue under the Dee Estuary. There are two main sets of faults running east to north-east and north to north-west respectively and the coalfield is divided into a series of blocks. Mining is, therefore, difficult and expensive except in Point-of Ayr Colliery, Flintshire, where the conditions are good and the inclination low. Water difficulties, due to the penetration of water-bearing faults, has led to the abandonment of many collieries in the past particularly in Flintshire, though coal has been mined in North

Wales since the fifteenth century. The coals are mainly of the medium caking type.

The Northern English Coalfields

The coalfield on the east, that of Northumberland and Durham (5, Fig. 72 and 76), is best considered as an entity, although the Tyne Valley which forms the geographical boundary between the Counties also forms the dividing line between the coking coals of Durham and the hard gas and steam coals of Northumberland. This is an areal

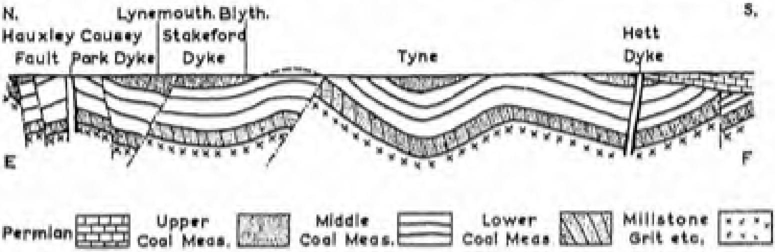


FIG. 76. SECTION OF NORTHUMBERLAND AND DURHAM COALFIELD IN THE DIRECTION E–F, FIG. 72

(Horizontal scale: ¼ in. = 6 miles. Vertical scale: ¼ in. = 3,000 ft.)

change, the individual seams changing their nature as they cross the Tyne.

The coalfield of the Coal Measures Age is triangular in shape and some 200 square miles in extent. In this region, also, the coals of the Lower Carboniferous become increasingly important to the north but although they represent a reserve for the future, perhaps of great value, they are as yet little exploited. They outcrop to the north and west and extend along the fringe of the Coal Measures proper from North Yorkshire, across into Cumberland and north to Berwick, covering an area of 1,500 square miles.

The coalfield is separated from that of Yorkshire by the Wharfe Anticline and the Coal Measures are overlain by Magnesian Limestone on the east coast of Durham, but this runs out at the mouth of the Tyne. Collieries sunk on the sea coast have to pass through these newer measures which are heavily water-bearing, particularly the running Yellow Sands at the base, and the freezing process of sinking is necessary and has proved an efficient though expensive method. The upper portion consisting of dolomitic limestone with open joints attains a thickness of 650 ft, beneath which are thin Marl Slates and the Yellow Sands up to 100 ft in thickness. Much of the Coal Measures are overlain by glacial drift which fills the hollows

of the Pre-Glacial landscape and in the buried valleys, like the Team Wash, attains a depth of 300 ft.

Igneous intrusions are more numerous in Northumberland than in Durham but the latter county has the Hett Dyke which traverses the southern portion of the coalfield from east to west.

The Durham Coalfield is not badly faulted and the faults are of small displacement with the exception of the Butterknowle Fault running east and west through Bishop Auckland with a throw of 720 ft to the south. Fairly large faults are more common in Northumberland, the three most important being the Ninety Fathom Dyke running NE.-SW., through Whitley Bay, the Stakeford Dyke running across the centre, east and west through Newbiggin, with a throw of 500 ft, and the Hauxley Fault, with a throw of 1,000 ft to the south, which forms the boundary of the Productive Measures to the North.

The general dip is a gentle one to the east with a possible gentle turn-up of the measures under the Permian cover seawards. Gentle folds cross the field running east and west giving a fairly deep syncline in the Wallsend area.

The Upper Coal Measures, with coals of inferior quality, reach a maximum of 750 ft in this trough. These coals are superior in Durham to the corresponding seams of Northumberland both in thickness and in quality.

The Middle or Main Productive Measures contain all the important coals with the Brockwell at the base and the High Main at the top with a bed of sandstone, "The High Main Post," as a roof. From this came the Grindstones, exported with coal from Newcastle to the Continent since the Middle Ages. The Middle Coal Measures are from 1,400–1,800 ft in thickness.

The main coals in ascending order are (Durham nomenclature first, followed by that of Northumberland where different)—the Brockwell, the Three Quarter, the Busty, the Harvey or Beaumont, the Hutton or Low Main, the Main or Yard, the Five Quarter, and the Shield Row or High Main, but correlation is difficult owing to a variety of local names and the misapplication of seam names for market purposes. In both counties the coals are at their best in the vicinity of the outcrops in the west.

In Durham those of the lower portion below the Hutton are the finest high rank coking coals in the country, with the possible exception of those of South Wales, with a volatile content between 25 and 30 per cent, ash 4 to 7 per cent, oxygen 3 to 5 per cent and sulphur below 1 per cent. In every direction from West Durham the rank becomes lower and the volatile matter increases to 35 to 40 per cent, the oxygen content from 4 to 6 per cent and sulphur to over 2

per cent. The alteration is areal and the variation in each seam is greater than the difference in seams at any point. The strongly coking coals are succeeded by gas coals, still strongly coking, the seams above the Hutton in West Durham being of this type.

In Northumberland the most important coals are in the upper portion of the Productive Measures such as the High Main, Bensham and Low Main. In both fields the seams in the lower portion tend to thin and to develop dirt bands to the east, and in Durham the top seams of the Lower or Ganister Measures and the Brockwell are not generally present east of the Great North Road, and the Busty deteriorates considerably.

The extension of the coalfield under the North Sea seems fairly well assured for a distance of six miles in Durham as workings already extend for a distance of three and a quarter miles. Local thinning of individual seams occurs and a gradual deterioration of seam thickness seawards will probably be revealed.

In Northumberland the seams become free-burning house and steam coals in the north with a volatile matter content of over 40 per cent. Under the sea the safety limit of 240 ft of cover between the seam worked and the sea-bed limits the reserves in the lower seams beneath the Bottom, which is the seam above the Beaumont, except in a trough extending about nine miles from Blyth to the Grangewood Fault where all seams below the High Main may be expected.

The Lower or Ganister Measures, between the Millstone Grit and the Brockwell seam some 120–300 ft in thickness, contain thin coals. These include the Victoria and Marshall Green seams which are between 2–3 ft in thickness, the former of excellent quality. As with the lower portion of the Middle Coal Measures, the seams thin eastwards and are only worked in the west near their outcrops. Fireclays and ganister are sometimes associated with these coals and simultaneous extraction may be resorted to in the future.

The Limestone Coals of the Lower Carboniferous, better developed in Northumberland than in Durham, have already been mentioned and will not be enlarged upon in this section.

THE CUMBERLAND COALFIELD is separated from that of Durham by the Pennine uplift and from the Lancashire and small Ingleton Coalfields by the older Carboniferous and Palaeozoic rocks of the Lake District. The exposed coalfield occupies the coastal area between Whitehaven and Maryport, has a width of some six miles, and then turns WNW. inland to Aspatria and towards Sebergham in a strip about two miles in width (6, Fig. 72). Below the Coal Measures thin coals occur but the main seams are confined to the Productive Measures about 1,000 ft in thickness.

The most important seam is the Main Band, reaching 15 ft in thickness in the undersea area, which splits into three separate seams, the Cannel, Metal and Thirty Inch to the west and north of the Derwent. In the same area the Yard Seam below increases in thickness to 5 ft and improves in quality in the Aspatria area. Some dozen seams between two and five feet in thickness are worked, including those mentioned above.

Above the Productive Measures is the Whitehaven Sandstone Series consisting of purple grey sandstones and shales forming the upper portion of the Middle Coal Measures. The general dip is to the west but the coalfield is badly faulted and folded with axes running NW.–SE.

Two regions of concealed fields occur, south of Whitehaven to St. Bees under the Trias and north of Aspatria under the Carlisle basin beneath 3,000 ft of Permo-Trias and 2,000 ft of Upper Coal Measures and the Whitehaven Series. Seawards the seams improve in thickness and quality and although the extension of the coalfield does not reach the Isle of Man it probably extends for a distance of fifteen miles from the coast. The faulting and folding of the exposed coalfield, which is pre-Permian, is expected to be reproduced in the undersea area.

Across the Carlisle Basin, on the Scottish side of the Border, is a small area of exposed Productive Measures, about one and a half square miles in area bounded on the south by a downthrow fault and on the north-east by an upthrow fault. This is known as the Canonbie Coalfield.

To the south the Upper Coal Measures are exposed consisting of red sandstones and shales some 1,500 ft in thickness with thin coals at the base. The Productive Measures consist of 1,000 ft of strata with eight seams from 3–9 ft in thickness and aggregating 40 ft. The Limestone Coal Group contains thin coals including three seams two feet in thickness. The reserves of this small coalfield under the Permo-Trias cover to the SE. may be considerable but an extensive programme of boring is required as information at present is meagre.

The Coalfields of Scotland

The coalfields of Scotland differ from those of England in that instead of the important seams being contained practically entirely in the Middle and Lower Coal Measures, in Scotland the important coals occur in two groups, the first in the lower portion of the Middle and the Lower Coal Measures (the Productive Coal Measures), and the second in the Limestone Coal Group of the Carboniferous Limestone Series of the Lower Carboniferous. The

Carboniferous Limestone Series consists, in ascending order, of the Lower Limestone Group from the Hurlet Limestone Coal to the Top Hosie Limestone, 300 to 1,000 ft in thickness, followed by the Limestone Coal Group, including the Edge Coals, from the Top Hosie to the Index Limestone, comprising 700 to 1,000 ft of strata, and, at the top, the Upper Limestone Group from the Index to the Castle Cary Limestone, 200 to 1,000 ft in thickness. The measures productive of coal occupy in all some 800 square miles and occur in seven main fields taking the form of broad synclinal basins which folding and faulting have further subdivided.

The Central Valley area has been subjected to spreads of volcanic material to a greater extent than any of the English coalfields, both Puy and Plateau type of intrusion took place in late Carboniferous and Permian to Tertiary times. Thus in some areas seams have been replaced by volcanic material but there is only very local anthracitation.

In both horizons the seams vary in number and thickness more rapidly than in the English fields so that correlation of seams is particularly difficult. Some of the smaller fields for example Sanquhar, have been deposited in valleys in the Pre-Carboniferous rocks. The area is generally covered by Glacial deposits.

The coals are highly bituminous and mostly of the gas and coking coal type including "splint" or cannels though locally good house coals occur such as the Bannockburn of Stirlingshire. Oil shales are exceptionally well represented. The Upper Coal Measures are absent and the Middle Coal Measures, consisting of Red Barren and Lower Productive Measures, are covered by Permian in parts of Ayrshire, Nithsdale and Annandale. The summit of the Productive Coal Measures is marked by Skipsey's Marine Band which contains many marine fossils also present in the Mansfield Marine Band of the East Midland Coalfield.

THE CENTRAL VALLEY COALFIELD stretches a distance of thirty miles from Bathgate to Barrhead (1, Fig. 77). The Productive Coal Measures occupy the central portion of the basin and the coals fall into two groups. The first, from the Splint Coal upwards, contains also the thickest seams including the Main, Pyotshaw and Ell which are present in the south-western portion of the coalfield round Glasgow, Airdrie and Hamilton. Those below the Splint Coal are thinner and eleven seams are worked including the Blackband, Virtuewell and Kiltongue coals, but they are generally present throughout, particularly to the east, and are of good quality.

In the Lower Carboniferous system although coals in other groups of this system are locally important, like the Castlehead and Quarrelton Thick Coals of the Calciferous Sandstone, the Limestone

Coal group contains the important seams which on the western side number from seven to eleven, from 2 ft–4 ft 6 in. in thickness, including the Meiklehill Main, the Wee and the Kilsyth coking seams. On the eastern side the group contains eight seams including the Bathgate Main and Jewel seams.

In the central portion of the field where the Limestone Coals underlie the Productive Coal Measures and on the southern margin

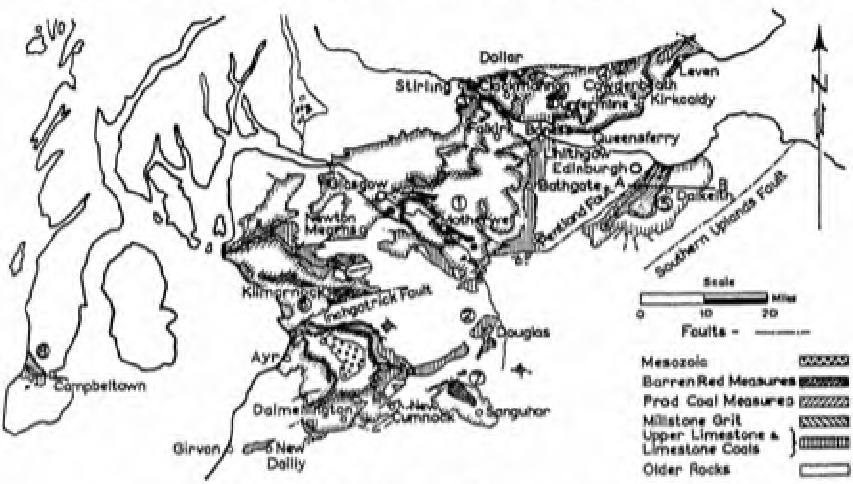


FIG. 77. SCOTTISH COALFIELDS

of the field, the Limestone Coals are poorly developed. This has proved a grave disappointment as these coals had been expected to replace the upper seams in the Productive Measures as these became exhausted.

The Limestone Coals are 286 yd in thickness at Cardowan, 440 yd at Kilsyth but south of Bathgate are only 240 yd thick. In the barren tract of the Hamilton-Wishaw area the thickness is reduced to 174 yd and at Stonehouse to 90 yd.

THE DOUGLAS VALLEY COALFIELD (2, Fig. 77) lies about fifteen miles SSW. of Hamilton and contains some twenty square miles of Carboniferous strata, detached from the Central Coalfield by Old Red Sandstone, in which the full Carboniferous succession is represented from the Barren Red Measures downwards. It is about six miles wide to the north where the Millstone Grit is exposed in a wide basin with the Carboniferous Limestone Series on the margin. On the western side, the Limestone Coal Group contains seven seams and on the eastern side eleven from 3–5 ft in thickness. To the south,

the Productive Coal Measures contain ten workable seams from 3–7 ft thick which correlate fairly well with those of the Central Valley coalfield, the Nine Feet correlating with the Virtuewell of the Central Valley Coalfield and the Seven Feet with the Splint.

THE NORTH-EAST STIRLINGSHIRE COALFIELD (3, Fig. 77), although continuous with the Central Coalfield to the south and across the Forth to the Clackmannan basin to the north, is generally considered as a separate coalfield. It is bounded to the NW., by the Ochil Boundary Fault, which also bounds the Clackmannan and Fife Field. It extends in a roughly triangular-shaped area from Stirling and Alloa in the north to Bo'ness in the east and Denny to the west.

This field has the bulk of its reserves in the Limestone Coal Group. There are no coals of workable thickness in the Lower Limestone Series and the only coals in the Upper Limestone are the Hirst Coals, the Upper about 4 ft and the Lower about 2 ft in thickness.

The Upper Limestone Group varies from 320 to 540 yd in thickness. The Millstone Grit varies in thickness from 220 to 380 yd, while the Limestone Coal Group varies from 260 to 360 yd. The latter consists of an upper portion 100 yd in thickness with three seams, followed by some 130 yd of lavas, interbedded with sedimentary rocks, followed by some 130 yd of sediments with six workable coals. The Productive Coal Measures occupy a synclinorium in the centre of the field divided into three minor basins.

The seams correlate well with those of Lanarkshire with the Virtuewell at the top and the Colinburn at the base, the intermediate seams being differently named in the two fields. The seams outcrop on both sides of the basin, the deepest portion of which is at Kinnaird.

THE FIFE AND CLACKMANNAN COALFIELD (4, Fig. 77), extends from Menstrie in the west to Leven in the east and is bounded on the north by the Ochil Boundary Fault, the Forth forming the other boundary and there are important reserves beneath it between Kirkcaldy and Leven which may be continuous under the Forth with the Lothians Coalfield (6, Fig. 77). The important coal reserves of Scotland are largely shared between these two fields. Eighteen seams more than 2 ft in thickness may be expected under the Forth.

In this coalfield all the coal-bearing formations are exposed in different portions of the field—the Barren Red Measures, the Productive Coal Measures, the Millstone Grit and the Carboniferous Limestone Series, comprising the Upper Limestone and Limestone Coal Groups. The most valuable seams are again in the Limestone Coal Group and in the Productive Coal Measures, but the Upper Limestone contains locally a few coals of workable thickness which have been exploited on a small scale.

The Lower Limestone Group and the Calciferous Sandstone Series contain thin coals but none of workable thickness, but the Lethainwell seam in the Millstone Grit has been worked near Dysart. The coalfield is divided by folding into a number of separate areas. In the west is the Clackmannan basin with Alloa in the centre, to the north of which is a patch of Barren Red Measures some 66 yd in thickness. The rest of the centre of the basin is occupied by the Productive Measures which attain a thickness of 300 yd. The borders on both the east and west carry exposures of Millstone Grit 370 yd thick and the Carboniferous Limestone Series up to 1,050 yd thick, those on the east being the thicker.

The Limestone Coals are well exposed in a broad belt in the east in the Valleyfield region with an inclination to the west and contain fourteen workable seams in a thickness of 450 yd with the Blairhall Main at the top and the Dunfermline Splint at the base immediately above the Johnstone Shell-Band. The Jersey-Diamond or Bannockburn Group of seams in the middle are among the more important coals. To the west these coals underlie the Productive Measures and have not yet been exploited. They are exposed in the extreme west but the number of seams is less, being seven.

The Productive Coal Measures, some 180 yd in thickness contains seventeen workable seams more than 18 in. in thickness, including the Upper Five Feet, 6–8 ft in thickness, the Nine Feet, 6–9 ft thick, the Lower Five Feet and the Coalsnaughton Main near the base, 2 ft–4 ft 6 in. thick.

This portion of the field is separated from that of Central Fife by an anticline through Balmule along which the Lower Limestones and Calciferous Sandstones Series are exposed. The Central Fife portion consists of a number of shallow basins. In the first basin, in the Cowdenbeath region, the Limestone Coals reach a thickness of 470 yd with 97 ft of coal, the Productive Coal Measures having been denuded.

An anticline through Lochgelly separates this area from the next, the Bowhill basin, in which the Productive Coal Measures are present and attain a thickness of 340 yd. The Millstone Grit with lava flows, 90 yd in thickness, the Upper Limestone Group, 290 yd thick with workable coals and the Limestone Coal Group, also about 290 yd in thickness, are also present.

An anticline runs from Burntisland in an NNE. direction into the NW. corner of the East Fife portion of the coalfield. The Limestone Coal Group contains sixteen seams of workable thickness, several of which unite to form the Fourteen Feet of Lochgelly at the Diamond-Jersey horizon in the middle of the Group. The Productive Coal

Measures, present in the northern portion of the Bowhill basin only, contain the Bogside Main Coal, 20 ft in thickness.

The East Fife area of the field has a broad arch on the west which is a continuation of the Burntisland anticline. From this the Upper Limestone Group dips to the east under Millstone Grit and Productive Coal Measures of the Dysart-Wemyss area. Here 170 yd of Barren Red Measures occur in a coastal strip about one mile wide.

The Productive Coal Measures vary from 520–360 yd in thickness, the Millstone Grit is 320 yd thick, the Upper Limestone Group is 250 yd in thickness in the NW., increasing to 400 yd SE. at Dysart and the Limestone Coal Group similarly increases in thickness from NW. to SE. from 170–240 yd. Only three workable coals occur in this Group in the NW. increasing to twelve at Dysart in the SE.

In the Productive Coal Measures some seventeen workable seams are present including the Dysart Main Seam which, in the Dysart region, attains a thickness of over 23 ft.

In addition to those enumerated above, small detached portions of this field also occur to the north of the Ochil Boundary Fault but none is yet of economic importance.

THE LOTHIANS COALFIELD (5, Fig. 77), on the south shore of the Firth of Forth consists of two parallel basins with a dome between running SSW.–NNE. through Prestonpans, that of the west, the Midlothian, being considerably the deeper. In extent it stretches eight miles along the coast between Portobello and Longniddry and extends inland fifteen miles in the west and nine miles in the east, the field, in effect, lying in a trough between the Pentland and Southern Uplands faults.

The western, Midlothian, basin contains both Productive Coal Measures and the Limestone Coals. In the eastern, East Lothian, basin the Limestone Coals only are of economic importance.

The Productive Coal Measures, important only in Midlothian, are never highly inclined and are known as the "Flat Coals" (Fig. 78). They attain a thickness of 500 yd in the west and decrease in thickness to the east. The Sherriffhall Fault, running east and west through Dalkeith, with a downthrow to the north of 500 ft, brings in an upper group of six workable seams above the Jewel seam, separated by 60 yd of measures barren of workable seams from a lower group of eight seams with the Jewel seam, 3 ft in thickness, at the top and the Seven Feet Seam, 4 ft in thickness, at the base. The upper group are only present north of the fault. About 140 yd of Barren Red Measures occur at Dalkeith in the west.

The Millstone Grit is represented by the Roslin Sandstones, Upper and Lower, of coarse red sandstone with marls and clays,

and varies in thickness from 250 yd in the west to 170 yd in the east.

The Upper Limestone Group locally has six seams of workable thickness, up to 5 ft, including the South Parrot Splint and the Group varies in thickness from 360 yd in the west to 100 yd in the east.

The Limestone Coal Group outcrops in a narrow exposure along the western boundary of the field, the strata here being very highly inclined, between 50° and vertical, and is known as the Edge coals (Fig. 78). The inclination is reduced in the deepest, central, portion

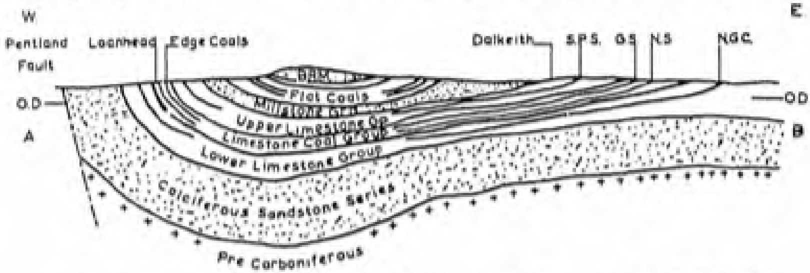


FIG. 78. SECTION OF MIDLOTHIAN COALFIELD IN DIRECTION *A–B*, FIG. 77

($\frac{1}{8}$ in. = 6,000 ft.)

Showing Highly-Inclined Edge Coals. *BRM*, Barren Red Measures; *SPS*, South Parrot Splint; *GS*, Great Seam; *NS*, North Seam; *NGC*, North Greens Coal.

of the basin and on the eastern and southern edges of the Midlothian basin, where the group is again exposed, the inclination is less than 25° (Fig. 78). In the East Lothian portion of the basin the seams are flat or gently undulating. In the west the Group is 340 yd in thickness and contains twenty workable seams including the Great, about 7 ft thick, the Gillespie, 4 ft 6 in., the Black Chapel, 4 ft 6 in., the Peacock, 3–5 ft, and the North Seam, 3–4 ft thick. The Group is reduced to 200 yd in thickness with twelve seams to the SE. of the Midlothian basin, while in East Lothian the thickness is 160 yd with nine workable seams. The same seam names are common to distinct coals in the Productive Coal Measures and the Limestone Coal Group.

The Lower Limestone Group has three coals which have been worked locally including the North Greens Seam, up to 3 ft 6 in. in thickness. The Group varies in thickness from 180–80 yd.

The Calciferous Sandstone Series beneath contains the Oil Shale and Cementstone Groups with a few thin and impersistent coals.

This coalfield shares the probable reserves of undersea coal, both Limestone Coals and Productive Measures, beneath the Firth of

Forth with the Fife Coalfield. Little is known of the folding and faulting of this undersea area, or of the effect of the old channel of the Forth before glaciation altered its course, but a thick deposit of Boulder Clay is to be expected which should greatly reduce the water hazard. Seismic geophysical prospecting has revealed that the danger from the old channel is negligible.

THE AYRSHIRE COALFIELD (6, Fig. 77), extends for a distance of thirty-seven miles from Lochwinnock in the north to Dalmellington in the south and from Troon on the coast to Glenbuck in the east, a distance of twenty-eight miles. Of this area some sixty square miles have been affected by igneous intrusions, particularly by whinstone (dolerite) dykes and sills. The field is separated from the Central Coalfield (Fig. 77), by Old Red Sandstone and igneous rocks.

The coalfield is divided into two by the Inchgotrick Fault downthrowing to the north and running ENE. from the coast south of Troon. The northern area is again subdivided into two by the Dusk Water Fault running in the same direction from Ardrossan. To the north of this fault the Productive Coal Measures are absent except for a few patches but the Limestone Coal Group reaches a thickness of 220 yd, thinning to the south. It contains four workable coals with the most consistent seam the Borestone, about 3 ft in thickness, at the bottom above the Black Metals. In the Upper Limestone Group above two coals corresponding to the Hirst coals of the Central Coalfield reach a workable thickness locally.

South of the Dusk Water Fault the full sequence from the Barren Red Measures downwards is present. These reach a thickness of 100 yd and the Millstone Grit, below the Productive Coal Measures, largely consisting of contemporaneous lavas, is variable in thickness from 20 — 170 yd. The Limestone Coal Group and the Productive Coal Measures both contain workable coals but the former is much thinner, only 95 yd, and contains only two coals. The Upper Limestone Group is similarly attenuated, only 27 yd. The Productive Coal Measures on the other hand are 180 yd in thickness and contain thirteen seams with the McNaught at the top and the Kilwinning Main at the base with three coals, the Splint, Turf and Wee, in the centre uniting to form the Main Coal at Galston in the east.

The Limestone Coal Group, where concealed by the Productive Coal Measures above, would appear to contain only two seams of workable thickness and to be subject to much spoiling by dolerite intrusions.

The largest and most important area economically is that in the centre of the field south of the Inchgotrick Fault to Dalmellington, and from the coast eastwards to Glenbuck.

There is a deep syncline in the northern portion round Mauchline, concealed by Permian strata 500 yd in thickness and 160 yd of lava, and a narrow syncline from Muirkirk to Glenbuck of Carboniferous Limestone overlain by Millstone Grit and heavily faulted.

In the south the area is divided up by faults running NE.–SW. In the north the Productive Coal Measures are some 220 yd in thickness, 250 yd in the west at Prestwick and 320 yd at Ochiltree in the SE. These encircle the Barren Red Measures and Permian strata, the former being some 500 yd thick in the north and 510 yd in the central, Ochiltree, area. The number of workable seams in the Productive Measures increases to the south and south-east in the Dalmellington and New Cumnock districts, from six in the north to eighteen in the south and twenty-three in the south-east in the New Cumnock area. The most important seams are the Main Coal, 5 ft to 6 ft 6 in. thick, the Ayr Hard, 4 ft to 7 ft, and the Knockshinnock Main, 5 ft to 12 ft 6 in. in the south-east.

The Limestone Coals and the Upper Limestone Group above reach their maximum development in the Muirkirk area to the east. The former is 120 yd in thickness with six seams, in descending order the Ell, 3 ft 6 in., the Seven Feet which splits NE. of Muirkirk into two, the Three Feet and the Four Feet, the Nine Feet, the Thirty Inch at the bottom of the Black Metals and the Six Feet with the Macdonald below the Johnstone Shell-Bed in the Glenbuck area.

The Upper Limestone Group is some 200 yd in thickness in this area with thin seams, of which the Cokeyard, 30 in. thick, above the Index Limestone and the Blue Tour 5 ft 6 in., correspond with the Hirst Coals of the Central Coalfield.

Westwards towards Mauchline the Limestone Coal Group is reduced in thickness to 50 yd and the coals tend to come together to form compound seams, for example the Upper and Lower Gass Water Coals, some 9 ft thick, above the Black Metals, and the 30 in. and 6 ft come together at Cronberry. Further west the Limestone Coals cease to be of economic value and locally the whole of the Carboniferous Limestone Series is absent. South of this barren area at Patna and south-east of New Cumnock the Limestone Coal Group is some 80 yd in thickness with the Patna Thick coal, up to 17 ft 6 in. in thickness, with variable seams below at Patna and 11 ft thick, corresponding to the Gass Water Coals, at New Cumnock.

At Dailly, near Girvan, and separated from the Main Ayrshire Coalfield, occurs a sharply-folded, elongated syncline of Limestone Coals, about five miles in length and about 100 yd in thickness with seven workable seams in the centre thinning to the SW. to 60 yd. The seams, in descending order, are the Main Coal, 5 to 7 ft thick,

the Ell, 3 to 4 ft, Parrot, 5 ft, Corral, 2 to 4 ft, the Craigie, 4 ft to 4 ft 6 in. and the Hartley Coal, 4 ft 6 in. to 5 ft.

THE SANQUHAR COALFIELD in Dumfriesshire (7, Fig. 77), about seven-and-a-half miles in length east of the Ayrshire Coalfield, occupies an irregular basin about seventeen square miles in area in the Ordovician rocks, the Southern Uplands Fault, with a throw of 400 yd, bounding the area on the north-east. In the centre the Barren Red Measures are 280 yd in thickness with the Productive Coal Measures below, some 260 yd thick, with five coals from 2 ft to 4 ft 6 in. in thickness. A thin band of Millstone Grit borders the area on the west and south but elsewhere the Coal Measures lie unconformably on Silurian rocks.

THE MACHRIHANISH COALFIELD, near Campbeltown in the Mull of Kintyre, Argyllshire (8, Fig. 77), consists of an area of perhaps nine square miles of workable coal. Coal Measures without workable coals, Millstone Grit, represented largely by volcanic rocks and the Carboniferous Limestone Series with the Limestone Coal Group, in which workings over one-and-a-half square miles have been opened out, abandoned and again exploited, comprise the exposure which probably extends under the sea to the west.

The coals which have been worked are the Killivan, 6 ft, and the Main Coal up to 12 ft in thickness but some eight seams are known aggregating 45 ft in 100 yd of strata.

QUESTIONS

1. Give an account of the Carboniferous System in the different parts of the British Isles.
2. What do you understand by Armorican-Hercynian folding? Explain how this has affected the location of the coalfields.
3. Give an account of the Upper Coal Measures.
4. Describe the succession and structure of a coalfield with which you are acquainted.
5. Give an account of the variation of rank of South Wales coals.
6. Draw a diagram illustrating the relation between the Yorkshire and the Lancashire and Cheshire coalfield.
7. In what respect do the coalfields of Scotland differ from those of England?
8. Distinguish between the Productive Coal Measures and the Limestone Coals in the Northern (Northumbrian and Scottish) coalfields.

CHAPTER VII

THE COAL MEASURES

COAL MEASURE ROCKS

It has already been remarked that the rocks of the Coal Measures are shales, sandstones, fireclays and coal seams with shales the dominant rock. The sandstones form the ridges and hills of the typical landscape of Coal Measure areas, with shales in the valleys. Blue is the prevailing colour of the shales and binds (metal or blaes) produced by finely disseminated iron sulphides; when grey the colouring matter is iron carbonate. A distinction is generally made between shales and binds or mudstones, the former are well laminated, split along horizontal bedding planes into thin layers, while this lamination is absent or poorly developed in binds. The composition of both consists of seventy to eighty per cent of clay or mud with twenty to thirty per cent of silt. When the latter increases to fifty per cent the rock becomes a silt-stone or "stone-bind" and with the same percentage of fine or medium sand, a sandstone results, known on the coalfields as "rock" or "post."

Numerous attempts have been made to fix limits of grain size in the different coal measure rocks in order to facilitate the standardization of rock descriptions. Phillips in the *Trans. of the Inst. Min. Engrs.*, Vol. **90**, mentions the following—

Pebbles	greater than 10 mm diam
Gravel and very coarse sand .	10 to 1 mm
Sand	1 to 0·1 mm
Silt	0·1 to 0·01 mm
Mud	less than 0·01 mm

The succession of rock types above a coal seam to the next seam in the succession shows remarkable constancy and is repeated again and again with little variation although there is never complete identity. The variation in the type of sediment is the result of the depth of water and type of material provided. The most variable members of the "suite" or "unit" of strata associated with the coal seam are the sandstones.

The coal swamp was situated in a subsiding area, subsiding not at a regular rate but quickly at first which resulted in the deposition of a fossiliferous shale, often with a transition sediment of "batts" or "bass," a black highly carbonaceous shale, or a coal band with a

high ash content at the top of the seam. The shale was succeeded by a sandstone or a stone bind as the delta again filled up and coal-peat formation was repeated (Fig. 79).

Immediately below the coal seam is the seat-earth or fossil soil upon which the vegetation forming the peat grew. These vary from soft unbedded, grey or white clays known as fireclays, "seggars" or "clunches," rich in silica and hydrated aluminium silicates, to ganister, a highly siliceous sandstone containing up to ninety-seven per cent silica. All are deficient in alkalis, calcium and iron which have been extracted from them by the roots of the plants which grew

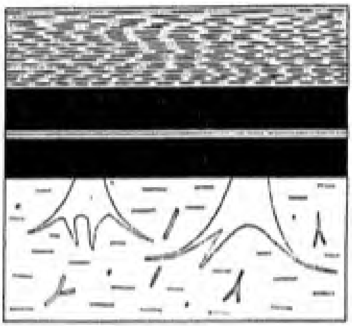


FIG. 79. A COAL SEAM AND ITS ASSOCIATED STRATA

In most cases, a coal seam has below it a bed of unstratified clay (fire-clay or seat-earth), with roots and rootlets and above it, well bedded shale with plant remains.

upon them and whose fossil remains, penetrating the seat earths, are generally extremely evident. They form the strongest evidence of the "*in situ*" theory of coal seam formation as opposed to the "drift" or "migration" theory of growth at some distance from the present position of the coal seam. It must, however, be realized that no hard and fast division exists between the two theories and both methods probably took part in coal seam formation.

The sandstones were deposited in times of flood and occur in lenticular masses and so are inconstant in thickness. They are often current or "false-bedded." Being deposited in erosion conditions they frequently remove shale above coal seams and sometimes the seam itself or the top portion of it producing a "wash-out" or local failure or thinning of the seam.

The type of sediment immediately above and below a coal seam is of great importance in the economic winning of the seam. A fine shale, a "batt" or a "clunch" may be so soft that it is "tender" or "short" and difficult to support at the coal face, while a soft clunch floor may swell or squeeze up, "lift," in the roadways thus reducing

the size of the road and, since the maximum lifting occurs in the middle, disturbing the rail tracks and necessitating their relaying. In order to preserve the strength properties of these beds above and below coal seams during the working of the seam, the science of "roof control" has been developed and has a great effect upon the economics and the safety of coal getting.

Coal Seams

Coal seams on examination reveal a banded structure, the appearance of each band being different from that above or below it. Others exhibit also a composite character, that is they consist of several individual seams separated from each other by bands or layers of shale or "batt."

The banding and the dirt partings in a seam are often characteristic and can be used for purposes of correlation over a fairly wide area. The banding of the coal is a result of difference in the vegetation which went to form the different bands, and to some extent, of the conditions existing when it was being converted into peat. Thus a coal seam has often a band of soft coal at the base above which is a band of bright coal followed by hard, dull coal in the upper portion with a bastard, high ash, coal band, a cannel or a carbonaceous shale band adjacent to the roof of the seam. Thick seams with numerous dirt partings often emphasize their composite character by splitting up into separate seams with the dirt bands between increasing in thickness to many yards of strata. Fig. 80 shows the splitting up of the Ten Yard or Staffordshire Thick Coal.

Most coal seams, except anthracite, exhibit three separate sets of division planes, a horizontal set corresponding with the bedding planes of sedimentary rocks and two others at right angles to the horizontal set and to each other. These vertical joints are known as the "cleat" or "cleavage" of the coal and are analogous to jointing in sedimentary rocks. One set is more strongly marked than the other and coal worked in a direction at right angles to this main "face" or "bord" cleat is easily got while that worked at right angles to the less strongly marked "end" or "headways" cleat is less easily worked. Coal faces at certain angles to the main cleat have particular names, thus at 45° to the cleat the face is said to be "on half and half," at 22½° "on long awn" and at 67½° "on short awn." When coal-cutters are used to "hole" or undercut the seam, the face will generally be "on end," that is with the length of the face at right angles to the main cleat, advancing in a direction parallel to it.

In most of the coalfields in this country the cleat runs in a direction NNW. and SSE. With the innovation of highly mechanized methods

of working, using cutters and mechanical loaders, less influence on the direction of the faces is exerted by the direction of cleat, and main and auxiliary roads are often set out with more regard to inclination than to cleavage, but in many cases the latter is still an important factor. Some seams exhibit a set of inclined fractures similar to fault planes but without any dislocation of the seam. These are known as "huggers," "slips" or "backs" and again may influence

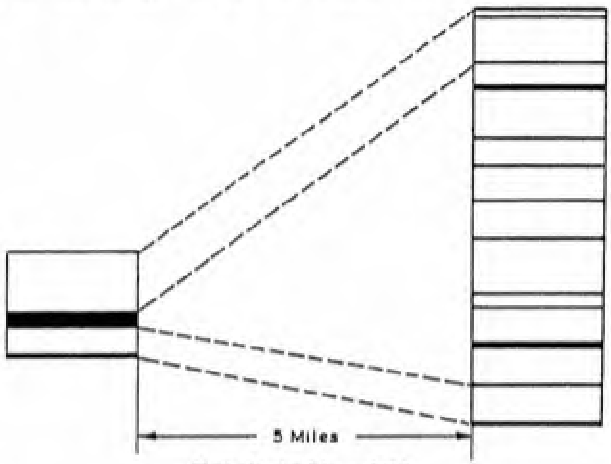


FIG. 80. THE SPLITTING OF THE THICK COAL OF SOUTH STAFFS. TO THE NORTH

the direction of working of the face. It is uncertain whether these were produced by geological agencies or whether these are fractures produced in the solid coal ahead of the working face by a concentration of stress there, induced by the extraction of the seam and the release of energy in the superincumbent strata above the seam, known as the "front abutment pressure."

Coal Formation

The "*in situ*" or "growth in place" theory of coal formation has now received almost universal acceptance for the majority of coal seams with the exception of cannels, bogheads, torbanites and a few other seams of the so called sapropelic type. The main reasons for this conclusion are as follows. First, the wide extent of individual seams, particularly when it is realized that what remains is often only a fraction of what has been removed by denudation following folding. Also the thickness and banded structure of the seam is uniform and

characteristic over a wide area. In fact the seams themselves are often the most consistent deposits in Coal Measure strata. Further, as already mentioned, the seat earth forming the floor of the coal seam is generally penetrated by rootlets now fossilized. Again there are rarely remains of aquatic animals in the coal seams and an absence of detrital matter, other than "cleat spars" in the cleavage planes which probably found their way in after the laying down of the peat. These circumstances are inconsistent with an origin involving drifting vegetation deposited in lakes by stream and flood action although this origin fits in with the composition and situation of the cannel coals.

The Coal Swamps or Peat Beds

Examination of peat bogs now growing in many parts of the world, particularly in deltaic conditions, postulates humic coal seams as the product of low-lying forest growths, very little above sea-level, in a subsiding area but continuous over vast areas. In short, a vast swampy area, akin to the Great Dismal Swamp of Virginia of the present day, but covering an area with the dimensions of the flood plain of the Amazon or the Ganges delta. The swamp area became cut off from the sea by sand or mud banks leaving an estuarine area of fresh or brackish water which was silting up and therefore very shallow. Water-loving plants like the mangroves became established in the shallow water, rooted in the silty banks and were of the *Calamites* and *Sigillaria* types (Fig. 57). These would supply the humus to build up a soil on which the giant Lycapods could grow, like *Lepidodendron* (Fig. 60), with a thick undergrowth of plants of the fern type such as *Neuropteris* and *Mariopteris* (Fig. 58). "Vitrain," the bright bands in "clarain" or bright coal was formed from the bark and woody tissue of these giant Lycopods as their trunks lay rotting in the stagnant, peaty waters. "Fusain" or "mother-of-coal" may have been formed from the twigs and branches partly rotted in the air before falling into the peat swamp, while the dull layers, or "durain" bands, in the coal were produced from macerated plant debris, generally waterlogged but occasionally dried out and so decomposed that only the most resistant cones, spores, cuticle (the outer skin or layer of leaves) and resins can be identified. It is evident that the Bright Coal or clarain, with vitrain bands, was formed by the coalification of vegetable debris where it grew, with no addition of detrital material, consequently the ash content of that portion of the seam which consists of clarain is low, the vitrain bands being particularly low in ash. The dull coal or durain bands probably consist of a mud of fine plant debris, with some detrital material

laid down on top of the coal peat when it was inundated by shallow water, so that durain has a higher ash content. It has often been remarked that the bottom bands of a coal seam are soft and dull consisting of plant fragments with an origin somewhat in the nature of leaf-mould. Above this comes Bright Coal with bands of vitrain with much larger plant fragments and woody structures retaining a compressed cellular structure together with both female and male spores (macro- and micro-spores). The top portion of the seam consists of dull coal with much spore material and plant residue.

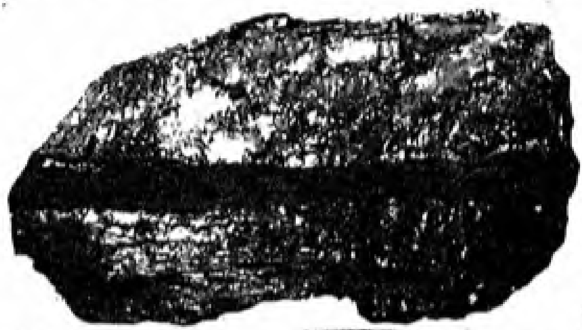


FIG. 81. AN UNUSUALLY THICK BAND OF FUSAIN IN A SOUTH WALES COAL
The specimen is about 8 in. long.

Between the bands is a soft, black, powdery material which readily soils the fingers and is known as fusain, mother-of-coal or mineral charcoal (Fig. 81). Microscopic examination shows it to consist of cellular tissue with opaque cell walls which distinguishes it from the cellular structures preserved in clarain, which are translucent. The cells may be empty or filled with mineral matter, ankerite or pyrites, and fusain has consequently a high ash and sulphur content, the former reaching thirty per cent.

Next to the roof is often the transition layer of bastard coal or batts representing the last vegetation or drifted vegetation immediately afterwards drowned by the renewal of subsidence during which the coal peat was overwhelmed and covered with successive layers of muds, sands, etc., until silting up allowed the re-establishment of vegetation and the renewal of coal peat formation and the genesis of yet another coal seam. In some cases the top layer of a seam consists of cannel or "splint" coal. This occurs in lenticular bands and results from erosion of the top peat layer with the formation of a local lake into which drifted plant debris in a finely divided state and in which fish remains often occur.

As successive layers of vegetation were piled up in the peat bog compression of the lower layers occurred, as it occurs also in peat bogs of the present day, the reduction in volume resulting from compression amounting to as much as eighty per cent of the original volume. When covered by further material in the form of mud and sand, which afterwards became Coal Measures strata, increased compression occurred and it has been postulated that at least 15 ft of vegetable debris was required to produce each foot of a coal seam.

On the other hand the origin of the sapropelic coals, cannels, bogheads and torbanites, is entirely different. The cannels consist of drifted vegetation in a highly disintegrated condition deposited in lakes in small clearings often on the surface of coal peat. They have no seat earths. They are dull and greasy in appearance with a conchoidal fracture. They are generally lenticular in shape, which is to be expected from their very local extent, are high in ash owing to detrital mineral matter being deposited with the vegetable mud, and the remains of fishes and other aquatic animals are fairly common. The torbanites and bogheads are similar in origin but are browner and tougher and they contain fossil algae.

Mineral Matter in Coal

This has three origins. First, all growing plants contain not more than 1 per cent of ash or mineral matter and this of course is inherent in the coal substance and cannot be separated by any coal-cleaning process. Secondly, a certain amount of fine mineral matter, such as clay, became entangled with the coal peat by infiltration or by wind action and became either disseminated generally throughout the seam or concentrated in the form of thin dirt bands between the different coal layers of the seam. In this case coal-washing can remove some of this mineral matter, particularly if intergrown coal and dirt is separated as a "middlings" product and is then crushed to disentangle the two and rewashed.

Vitrain, produced from the bark and tissue of fallen tree trunks, has little added or "adventitious" ash and therefore the ash content of these bands or layers in a coal seam is generally little more than the inherent plant ash of one per cent. Similarly the clarain or "brights" which contains a high proportion of vitrain, also has a low ash, but owing to the presence of cleat planes containing spar in the form of ankerites, (carbonates of calcium, magnesium and iron), at fairly close intervals, the ash content is of the order of three per cent. The durain or dull coal bands generally contain less cleat spar as the cleat planes are further apart in these than in "bright" coal but more infiltrated clay minerals became entangled in the macerated plant

debris in peaty water from which it was derived and consequently the ash in durain is seldom less than four per cent and may be considerably higher. Fusain generally has a high ash content since the wood cells, of which it is normally composed, contained not carbonaceous matter like the wood cells in vitrain but mineral matter, often ackerites or pyrites.

Variation of Thickness and Splitting of Seams

On what was originally the edge of the coal swamp conditions for peat formation would not be so favourable and there would be a greater chance of admixture with detrital, sedimentary material. This explains the thinning and deterioration of seams encountered on the edges of the original peat areas. A further cause of thinning was local elevation of part of a coal swamp by earth movement and erosion by wind and weather of the upper portion of the peat before general subsidence again took place and the whole area was buried. In addition elevation would generally render conditions unfavourable for peat formation so a thinner seam would result in any case in the area elevated. This deterioration and thinning of seams is common in most coalfields and an example is that of the Top Hard-Barnsley seam as it passes into West Yorkshire as the much inferior Warren-house seam.

It is extremely probable that the Lancashire and Yorkshire Coal-fields were portions of an extensive coal swamp with a centre some-where in the region of the Pennines, so that a larger and richer portion has been denuded following the uplift. This is borne out by evidence that secondary or impersistent seams are absent on the west of the Lancashire and on the east, concealed area, of the Yorkshire Coalfield. There is also some evidence of seam deterioration, though not necessarily thinning of seams, in the same directions. This is consistent with a swamp centre somewhere in the locality of Buxton as the centre of a complex Coal Measure age geosyncline. This probability is important in assessing the possible reserves of coal in the concealed areas of both coalfields. The seams of the Durham Coalfield also appear to thin in an eastward direction and under the sea, the seams below the Hutton being particularly affected, but the Main, Seven Quarter and Five Quarter above are also involved.

Thinning of seams has also been remarked very frequently under a "rock," sandstone, roof and also when sandstone forms the floor of the seam. It is likely that, in the latter case, this is because the original sandbank would be higher and probably better drained than the surrounding swamp and therefore a poor site for peat accumulation. As subsidence proceeded, however, the sandbank would

become engulfed in the swamp but the coal seam produced would be thinner over the area covered by the sandbank.

Streams meandering across the coal swamp would cut a channel through at least the upper portion of the peat replacing it by silty

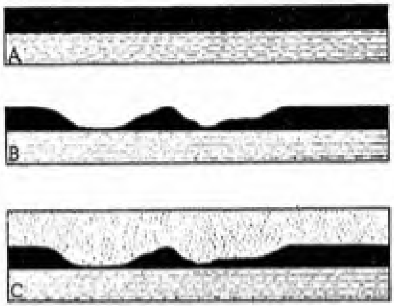


FIG. 82. EROSION OF COAL PEAT BY A STREAM

A layer of vegetable debris that ultimately became a coal seam was in part eroded. *B*: as a stream cuts its way through the swamp and when subsequently covered by sediment. *C*: the stream exhibits local interruptions.

sediment (Fig. 82). This would afterwards result in a thin seam along the sinuous course of the stream. If the whole of the peat was removed, a "washout," again following the original course of the stream, would be produced. These are common in all the coalfields. In other similar examples a split seam may rejoin, the two thin portions of the original seam rejoining on the other side of the

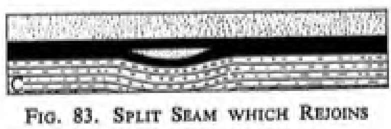


FIG. 83. SPLIT SEAM WHICH REJOINS

original valley and the enclosed silt, being less compressible than the peat, producing a lenticular mass of sandstone between the seams (Fig. 83).

The differential movements of the different portions of a coal swamp were also the cause of the splitting of coal seams. Dirt partings between the different layers of a seam may thicken, often rather quickly, and the coal layers may then become separated by

many yards of sedimentary strata, the coal layers then taking on the appearance of separate individual seams. An outstanding example is the splitting of the Ten Yard or Thick Coal of South Staffordshire to produce the separated seams of Cannock Chase already referred to and shown in Fig. 80, but splitting of seams is very common in all coalfields.

Differential subsidence of a portion of the swamp through earth movement produced a deeper area into which the streams meandering over the coal swamps collected and deposited mud and silt. This would in time cause silting up of the depressed area and coal forests and peat production would be re-established. During this period peat accumulation would continue in the stable area and would again spread over the formerly depressed area. If the silting up was rapid there may be little loss of total seam thickness, but if silting up took place slowly a portion of the thick seam, continuously deposited in the stable area, may be absent in the split seam area. As folding commonly occurs repeatedly along the same axes, it is evident that splitting may take place a number of times as evidenced by the Thick Coal illustrated in Fig. 80.

In addition to the washouts already mentioned, which affect a single seam only and which may vary from a few feet in width to as much as ten miles, very extensive and deep "washes" have been encountered which took place at a considerably later date than that of the peat formation and may affect two or more adjacent seams. There are also "rock faults" produced by earth movement which caused a mass of heavy, partly consolidated sand to gouge out and replace the soft unconsolidated peat not yet coalified. "Stringers" of coal may be found intermingled with the sandstone. Some seams are particularly liable to these occurrences, especially those with a sandstone roof. A further possible cause of these interruptions was the rupture of the peat when in a partly consolidated, tough condition by tectonic movement, and the running in of quick-sand from above the peat bed into the fractures or tears produced.

River erosion and glacial action during and immediately preceding the Ice Age has led to the erosion of coal seams, the effect being covered up by glacial drift deposited during the Ice Age. Such a washout occurred in the Team Valley in Durham and has been encountered over a width of a mile and a half in the working of the Hutton Seam.

Faults

Faults produced by folding and earth movement in the coalfields of this country are commonly of the normal or "tension" type with a

hade of 70° to the horizontal, although overthrust or reversed faults are not unknown particularly in South Wales. They are however much more common in the disturbed Pas-de-Calais and Ruhr Coalfields of Europe. In the majority of the British coalfields the faults occur in two sets at right angles parallel to the dip and to the strike of the seams and also parallel to the main axes of folding which probably also has an effect on the direction of cleavage of the coal. This frame-like type of faulting has been explained as the result of torsional stress. Many of the large faults are not continuous but overlap, one running out and another commencing a short distance away and running parallel to the direction of the original fault. Branching and splitting up is common and although the general trend is in one or other direction at right angles, local swinging or change of direction is frequent.

Large faults often form the real or apparent boundaries of a coalfield, real if they bring an older formation against the Coal Measures, i.e. large upthrow faults relative to the Coal Measures. This occurs when Millstone Grit and the Devonian are brought up against the Coal Measures at the northern boundary of the Yorkshire Coalfield and the Fife Coalfield of Scotland respectively. The large downthrow faults, bringing for example Trias against the Coal Measures as in the North Staffordshire Coalfield, form only an apparent boundary to the coalfield as the Coal Measures may be, and probably are, present under the newer deposits. Much will depend on the relative dips of the two systems and the amount of denudation of the Coal Measures which occurred during the period represented by the unconformity between the top of the Carboniferous and the base of the Permo-Triassic. The Upper Coal Measures evidence the change taking place at the end of the Carboniferous from deltaic and lagoonal to Continental conditions; and they also herald the beginnings of the Hercynian orogenetic or "mountain building" earth movement which, away from the coalfields, produced intense folding and overthrusting, but being less intense, bent the coalfields into a series of broad synclines and anticlines. During the Continental conditions which followed considerable denudation took place, particularly from the summits of the folds, and in places as much as 12,000 ft of strata was eroded before the deposition of the Permian or Triasic strata. This erosion was of varying degree, increasing to the south so that the Permian is deposited on the East coast successively on Upper Coal Measures near the river Wear, Middle Coal Measures near Durham City, Lower Coal Measures near Darlington on Millstone Grit near the river Tees and on Lower Carboniferous near Knaresborough.

The folding, faulting and intrusive dykes accompanying these earth movements did not, in the majority of cases, affect the Permian or Trias which were deposited in the calm following the storm and have a slight inclination only. Some posthumous faulting has however occurred, producing faults with a decreased throw in the Permo-Trias. In the Coal Measures themselves faults affecting the lower seams only are encountered but these have a relatively small throw.

The effect of faulting in accentuating or diminishing the water problem in collieries depends on the beds traversed by the faults and whether the fault "leader" or crack is open or filled with impermeable "leather-bed" or clay. Faults of the former type tend to become drainage channels for underground water and particularly when thick porous water-bearing sandstones, either Triassic or Coal Measure, are traversed by the fault, its exposure in underground workings may cause a dangerous inrush. Collieries have been lost, with fatalities, from this cause. On the other hand a fault may form a reliable barrier to prevent water from drowned old workings to the rise penetrating new workings to the dip.

The igneous rocks of the dykes and sills associated with the Hercynian folding, which were in a few cases intruded into or near certain coal seams of the Durham and Northumberland coalfield and the Central Valley coalfields of Scotland, cause alterations of the seams in the vicinity of the intrusion. The seam may be altered to a worthless mass of cinder or it may, in the locality, be thermally metamorphosed to a higher rank through loss of volatiles. The alteration generally occurs abruptly and the area affected depends upon the initial temperature of the intrusion.

THE RANK, COMPOSITION AND CORRELATION OF COAL SEAMS

The type of coal in a coal seam, as exemplified particularly in the composition of the bands of which it is composed, depends on the palaeobotanical make-up of the particular coal swamp from which it is derived.

The rank of the coal is something entirely different. It is a function of the degree of coalification which has been accomplished in that particular seam. That is, it is the measure of the distance along the road stretching from plants to anthracite which that particular seam has travelled. Increasing rank of coal is marked by increase of carbon and decrease of oxygen content.

The following are the compositions of the most important members of the range of fuels between wood and anthracite, on what is known as a dry ash-free (or mineral-matter-free) basis, which means that

moisture and ash have been eliminated before the analysis was carried out which divided the composition of the fuel into its separate elements. This process is indicated by the symbols A.F.D. or D.M.M.F. in the heading of the analysis.

Fuel	Carbon	Oxygen	Hydrogen	Nitrogen and Sulphur	Calorific Value (B.t.u./lb)
Wood	50	42·5	6·0	1·5	7,500 (air dried)
Peat	56·8	34·8	6·4	2·0	8,000 (air dried)
Lignite	73·6	19·0	5·4	2·0	12,700
Sub-Bituminous	78·2	14·9	5·4	1·5	13,500
Bituminous	85·9	7·2	5·5	1·4	14,300
Semi-Anthracite	89·6	4·5	4·3	1·6	15,200
Anthracite	93·9	1·5	3·4	1·2	15,300

Examination of the chemical and physical properties of this range of fuels indicates that increase of rank is accompanied by—

1. Increased darkness of colour.
2. Increased lustre.
3. Decreased transparency to light in thin sections.
4. Increase of calorific value.
5. Increase of carbon percentage.
6. Diminution of moisture content from 50 per cent in wood, 90 per cent in peat *in situ*, 30–60 per cent air dried, 25 per cent in lignite, 2½ per cent in bituminous coal and 1 per cent in anthracite.
7. Decrease of volatile matter content.
8. Decrease of oxygen content.

The variation of oxygen content, which is very constant in modern plants, from 50 per cent down to 1½ per cent in anthracites, cannot be due to variation in original plant composition and rank would appear to be determined by reduction in oxygen percentage. If oxygen and carbon contents of fuels be plotted as in Fig. 84, the points will lie in a very narrow band about the curve shown and it is, therefore, apparent that geological change producing coalification is associated with oxygen loss. Age alone cannot explain rank since there are Tertiary anthracites and the same seam may vary in rank progressively when followed across a coalfield.

Increased Rank is produced by increase of pressure and temperature and both these are associated with increase of depth. The pressure increases approximately 1 atmosphere (14·7 lb/in.^{2}) for every 12 ft of depth and the temperature in accordance with the geothermic gradient of the locality, which in the British Isles averages 1°F for every 63½ ft increase of depth. The maturing process

associated with rank increase in coals is accompanied by the elimination of CO_2, H_2O and methane, CH_4, from the coal substance but the process is as yet not fully determined.

Two geological causes of increase of rank may be distinguished. In the commonest, increase in rank accompanies increase of original depth of burial of the coal seam, which may or may not be related to

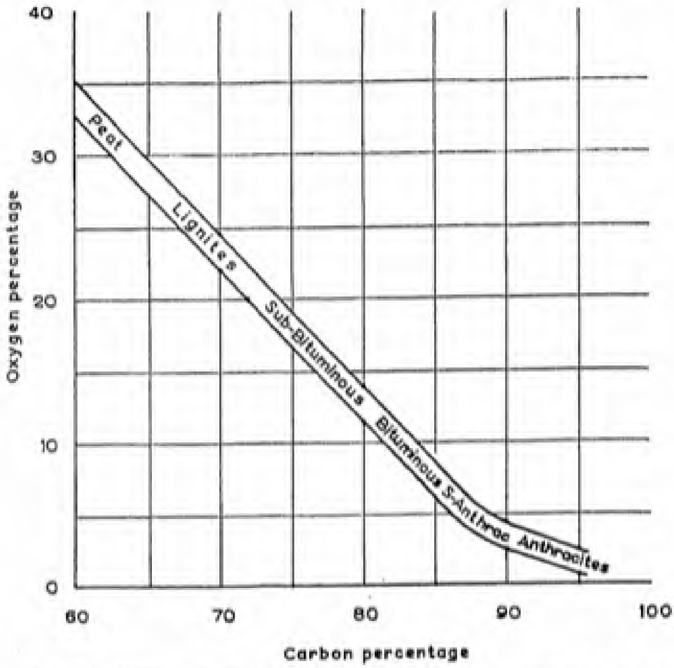


FIG. 84. VARIATION OF OXYGEN WITH CARBON CONTENTS OF COALS

the depth at which it is now mined since denudation may have removed much of the original cover. Also if one seam in a coalfield increases in rank all others above and below it alter in rank sympathetically so that the effect is an areal one and not confined to one particular seam. Hilt's Law, which holds for at least the great majority of the coalfields of the world, expresses the relation of rank to depth as follows—"In a vertical succession at any point in a coalfield the rank of the coals increases with depth." Increase of pressure is probably of greater importance than increase of temperature in producing increase of rank, but as mentioned above, both are operative simultaneously.

The second method is increase of rank produced by pressure and perhaps temperature induced by folding associated with earth movement and is thus a type of thermo-dynamic metamorphism. The increase is gradual and progressive and again areal. The variation of rank of the coals of South Wales is of this type (Fig. 85), as is the anthracitation of the Cretaceous and Tertiary coals of the Western Coalfields of the United States by the folding which produced the Rockies. The maximum tectonic movement is not always directly associated with maximum increase in rank, since greater pressure

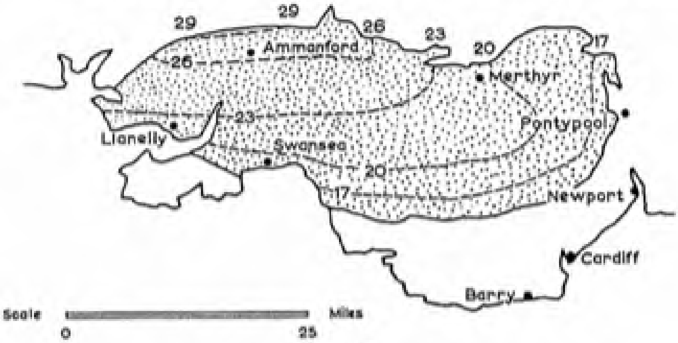


FIG. 85

Illustrating the Lateral Passage from Bituminous Coal to Anthracite (Increase of Rank), of one S. Wales Coal Seam. The seam (the Nine Feet and its equivalents) becomes progressively poorer in volatile matter and richer in carbon when traced from SE. to NW. The numbers 29–17 are C/H ratios of the coal in the respective areas and the lines associated with them are iso-anthracitic lines—i.e. lines joining points where the coal possesses the same C/H ratio, that is, has reached the same degree of anthracitization or rank.

may be produced in the septa or sides of the fold although the maximum displacement of beds may occur in the arches and troughs.

Local anthracitation is commonly associated with intrusions of igneous rocks into or near coal seams as in the Central Valley Coalfields of Scotland. The effect is sudden and the area of seam affected depends on the temperature of the igneous rock when it was intruded and to a lesser extent on the magnitude of the intrusion. In many cases instead of having increase of rank impressed upon it the seam in the vicinity of the intrusion is reduced to a cindered worthless mass.

A knowledge of the structure of a coalfield is important both in the estimation of future reserves and in the planning of future workings to exploit the seams. Correlation of seams over an area and from one area to another then becomes necessary. The problem also presents itself when boring in a virgin area and when recovering a seam displaced by faulting.

The methods of correlation adopted are many and varied and are used simultaneously, much depending on the distance between the points to be correlated as to which method in a given case gives the most reliable result.

The plants associated as fossils with the roof shales gives a broad classification of the Coal Measures, in descending order, into—

Radstockian corresponding approximately with the Upper Coal Measures.

Staffordian corresponding with the transition measures between the Middle and Upper Coal Measures.

FIG. 86. THIN SECTION, AT RIGHT ANGLES TO THE BEDDING, OF COAL CONTAINING SPORE-CASES (× 10)

Yorkian or Westphalian corresponding approximately with the Middle Coal Measures.

Lanarkian corresponding approximately with the Lower Coal Measures and the Millstone Grit.

The identification is based upon the types of plants present and the proportions of all plants which occur. The method, however, is not much used for detailed identification within short distances. Closely related is the method of correlation by megaspore (female), and microspore (male), content (Fig. 86).

Correlation by megaspores depends both upon certain spores being characteristic of certain seams and also upon the fact that the spore content of a seam is constant within reasonably fine limits. The identification of individual types of megaspores is by shape, ornamentation and proportions. The microspores are much smaller and must be extracted from a "pillar" sample of the seam by solvents. The different types are then separated and counted on a microscope

slide and the percentage of each type present is ascertained and plotted on a block diagram. Each seam has its characteristic microspore block diagram.

At various periods during the Coal Measure Age incursions of the sea occurred and in the thin shales then laid down appears a characteristic marine fauna. Five such bands occur in Lancashire and Yorkshire and are of the utmost importance as landmarks in the Coal Measure sequence as they are widespread over large areas. They are of particular importance in sinking and borings.

(a) (b)

FIG. 87. COAL MEASURE LLAMELLIBRANCHS

A. Anthraconaia adamsi (Salter) from the Soap Vein Shales Ebbw Vale, Monmouthshire. *B. Carbonicula acuta* (Sowerby), from the Blue Vein Shales, Ebbw Vale.

As with the fossil plants, but with much greater certainty, the freshwater mussels or lamellibranchs, *Carbonicula*, *Anthraconauta* (Fig. 87) and *Naiadites*, occurring in ironstone bands above some seams, may be used for correlation which is based both on certain species with a limited range and upon the different proportions of all "mussels" present. The characteristic species which have been used successfully are, in descending order—*Anthraconauta tenuis*, *A. phillipsi*, *A. pulchra* and *Carbonicula similis* together, *A. modiolaris*, *C. communis* and *A. lenisulcata*.

For generations the following lithological methods have been adopted for correlation purposes by practical miners and engineers on the coalfield particularly over short distances. Firstly, the characteristic constitution and banding of the individual seams, and

secondly, the position in and the arrangement of the sequence of strata or suite of rocks associated with each individual coal seam and their relation to the marine and freshwater mussel bands already mentioned.

It will be realized that correlation of the Lower and Middle Coal Measures is easier than in the Upper Coal Measures in which fossil distribution is very much more sparse.

QUESTIONS

1. Give some account of the banded structure of coal seams.
2. Give an account of the mode of formation of coal seams.
3. Give an explanation of the variation of thickness and the splitting of coal seams.
4. Give an account of the types of faulting encountered in the coalfields of this country.
5. What do you understand by the "rank" of coals?
6. Give an account of one method of correlating coal seams.
7. Give an account of the use of fossil "mussels" in the correlation of coal seams.
8. Give some account of the importance of Marine bands in the correlation of coal seams.

CHAPTER VIII

THE MESOZOIC ERA AND LATER

The New Red Sandstone System

THE continental conditions heralded by the red rocks of the Upper Coal Measures were established in this period, the prevailing colour of the rocks being red, indicative of arid desert conditions and absence of vegetation. The colour is derived from dehydrated iron oxides produced by weathering. In normal conditions these are attacked by humic and other organic acids from decaying vegetation but these are absent in desert conditions and the oxides remain to colour the eroded material. In addition, wind-blown millet-seed sandstones occur and deposits of gypsum and rock salt.

In the period represented by the unconformity between the Carboniferous and Trias great earth movements occurred on the Continent, known as the Hercynian Revolution, which produced intense folding and overthrusting in Southern England with fold axes trending E.–W. and at the same time the Pennine anticline was uplifted, probably along an older line of folding marking a continuation of the ancient Charnian axis. Accompanying these orogenic movements were igneous and volcanic activities evidenced by the granite bosses and mineral veins of Devon and Cornwall, the toadstones and mineral veins of Derbyshire and the dolerite Great Whin Sill and mineral veins of Durham, Northumberland and Cumberland. The folding and faulting are responsible for the preservation and the detached condition of the British coalfields in the synclinoriums or basins in which they are now found. But the heavy denudation which occurred before the deposition (unconformably on the eroded Carboniferous landscape) of the lower division, the Permian, of the New Red Sandstone, now buried under many thousands of feet of New Red Sandstone in the deeper concealed coalfield areas of the Nottinghamshire, Yorkshire and the Cheshire basin, was responsible for the loss of a high percentage of potential coal reserves. Particularly on the eastern side the regularity of the base of the Permian indicates that denudation had reduced the Upper Carboniferous landscape almost to that of a peneplain from Tynemouth to Nottingham.

The continent to the north and west of Europe remained, indeed this continent albeit with a shifting coast-line, would appear to have

been in existence from Cambrian to Tertiary times, with sea to the south and east; and the accumulating products of denudation and wind and torrent-borne material from the Hercynian mountain range was deposited on an area of dry land of relatively low elevation or into shallow land-locked inland seas of the Caspian and sea of Aral type, on the north-east coast from Nottingham to the Tyne. Conditions were unfavourable generally to the development of an extensive fauna or flora, many of the Carboniferous genera died out and those which remained were impoverished through unfavourable conditions such as increasing salinity in the land-locked seas and absence of vegetation in desert conditions. Tracks of amphibians like the impressions of an outstretched hand left by labyrinthodonts occur in the Keuper shales, reptiles attain importance locally and the first mammals occur in this Period. To the south and east the marine facies was very strongly developed with the production of massive dolomitic limestones which give their name to the Dolomites of the Tirol.

The New Red Sandstone System has been divided into two main subdivisions, Permian and Trias, of which the principal formations are—

Trias	Rhaetic Series Keuper Series Bunter Sandstone and Pebble Beds
Permian	Magnesian Limestone Lower Sands and Breccias

The exposure in Britain is considerable. Starting on the Devonshire coast it runs in a northerly strip to spread out in the Midlands covering the concealed coalfields and filling the deep Cheshire basin until at the base of the Pennines it divides into two strips up the east and west sides to the Tyne and round the north west of the Lake District with a break at Morecambe Bay. In Scotland and in Ireland only small isolated patches are exposed.

The Permian deposits are different on the east and west sides of England. In the east the concealed coalfield is buried beneath 4,000 ft of New Red Sandstone (Trias and Permian) immediately east of the Trent. In Nottingham wedges of Bunter and Keuper overlap a wedge of Permian and rest directly on Carboniferous and older rocks in Derbyshire and Leicestershire. The ancient ridges of Charnwood and the Longmynd confined the terrestrial deposits to the north until a sufficient thickness had been laid down to overtop the ridges with the upper beds. The overlap of the higher beds on to older rocks took place in this manner. The Cheshire basin with its salt beds, won by brine pumping, downfolded as it filled with sediment. At

Plumley, 2,500 ft of Keuper have been penetrated by boring, while at Heswell, on the Wirrall, 2,200 ft of Bunter has been proved.

The Permian of the north-east coast has the Yellow Sands at the base entailing the use of the expensive but effective freezing system of sinking to enable colliery shafts to penetrate them and the Magnesian Limestone with its open fissures. The latter is a concretionary dolomite deposited in a land-locked sea, the deposition of dolomite indicating extreme salinity. Concretionary nodules of calcite occur in the "Cannon Ball" Limestone exposed on the coast between the Wear and Tyne. On the west side, in Cumberland, the Permian rocks are of completely different origin. The Penrith Sandstone contains two thick bands of Brockram consisting of scree-breccia of angular fragments of Carboniferous Limestone. The band at the base attains a thickness of 1,500 ft. The sandy portion consists of bright red desert sand with millet-seed and recrystallized sand grains. Near Manchester the Permian is represented by the thick Collyhurst Sandstone up to 800 ft in thickness with the red and variegated Manchester Marls above.

The lower division of the Trias, known generally as the Bunter, although absent to the south on the Devon coast, consists of reddish-brown to yellow sandstone known as the Lower Variegated Sandstone. This is succeeded by the Pebble-beds, consisting of yellow or brown pebbles, larger to the south and diminishing to the north, of quartzite or grits from the Ordovician and Devonian, the majority of which appear to have come from the south and a lesser number from the west. Above this comes the Upper Variegated Sandstone, finer in grain and bright red in colour. The upper division is known as the Keuper, the lower portion of which consists mainly of sandstone, strongly false-bedded indicating rapid deposition, from which water supply is obtained by pumping from large diameter bore-holes, over 30 in. in diameter, using vertical spindle and submersible pumps.

The upper portion, known as the Keuper Marls, consists of bright red marls and shales in which gypsum and rock-salt occur in workable quantities in Worcestershire, Cheshire and at Billingham near Middlesbrough. In Nottingham and Yorkshire and on the southern border of the exposed Lancashire coalfield sinking of collieries in the past twenty years has been, and in the future will be, through New Red Sandstone deposits. Both the freezing and the cementation processes may find application, the former where Permian and the latter where Permian and Triassic rocks have to be penetrated. The later process consists in the injection of cement into the pores of the heavily watered sandstones, thus forming a watertight plug through which the shaft is excavated.

The topmost division of the New Red Sandstone System is the Rhaetic which marks the transition to the next system, the Jurassic. Before its deposition the configuration of the land had been denuded down to a peneplain and then the sea inundated the land suddenly. This is indicated by the fossil fish remains of the Basal Bed resulting from the destruction of the fish life by the sudden change of conditions occasioned by the marine incursion and by the uniform thickness of the Rhaetic, about 40 ft, and its widespread uniformity. The red colour of the Triassic rocks changes to anaemic greens and greys of the Rhaetic which consists chiefly of marls, laid down under marine conditions. Ammonites, though present in contemporaneous thick deposits in southern Europe, are not found in this country.

The Jurassic System

Although the beginning of the Mesozoic era is taken at the beginning of the Trias, thus dividing the New Red Sandstone period into two different eras, yet the characteristic strata conditions and fauna of this era are better typified in the two periods that follow, the Jurassic and the Cretaceous.

The end of the Trias marked by the Rhaetic occurred suddenly with a widespread marine inundation and both the Jurassic and Cretaceous rocks, though generally of a marine type, are those laid down in a continental shelf sea area subject to rapid fluctuation of depth producing also deltaic and estuarine conditions and occasionally lacustrine and even terrestrial areas. These fluctuations were due to mild earth movements, more strongly marked on the Continent where they determined the structure of the Ruhr and Campine Coalfields, known as the Saxonian or Cimmerian movement occurring along a NW.–SE. axis, a continuation of the ancient Charnian axis which produced also local unconformities.

The NW. continental land mass still existed and over East Anglia was an island or peninsula which was not submerged until the Chalk Sea spread over it at the end of the Cretaceous period and deltaic conditions including forests and peat swamps bordered the NW. continent. Near the end of the Jurassic Period an uplift occurred which cut off the sea of Yorkshire and Lincolnshire from a basin in the SE., in which fresh-water lake conditions were established and the limestone of the Purbeck (Upper Jurassic) and the Wealden lacustrine deposits were laid down. Further movement occurred and marine conditions transgressed over a wider area than in Jurassic times and the Cretaceous overlapped the Jurassic in many places on to older rocks.

The Jurassic is exposed as a belt across England from Weymouth

to the mouth of the Tees, the belt being of greatest width near Leicester. The area of deposition was widespread and only a small portion remains but patches were preserved, often by Tertiary lavas, and occur in Scotland (Brora), the Hebrides and in Ireland.

FIG. 88. AN AMMONITE FROM THE OOLITES, *Ammonite humphriesianus* (SOWERBY)
From the Inferior Oolite of Dundry; about one-third natural size.

The characteristic deposits of the Jurassic are clays and limestones, the latter being better developed to the south and often being replaced by clays in the Midlands and the north. The dip is generally to the east or SE.

The succession has been divided into, in descending order—

Upper Jurassic .	. clays with shelly or coralline limestones and sands
Middle Jurassic .	. the Lower Oolites
Lias	. Limestones and clays

The flora and fauna of the Jurassic are distinctive, the former is associated with deltaic and terrestrial deposits and is rich in cycads and ferns. Reptiles were plentiful including the gigantic *Ichthyosaurus* and *Plesiosaurus*, Dinosaurs and the flying Pterodactyls. In Germany the earliest birds and in this country the earliest mammals occur in this Period. The fossils used for zoning and correlation, however, are mollusca, cephalopod ammonites (Fig. 88), and belemnites are also

common. Corals are abundant in the limestones, reefs flourished along the shore.

The Lias, on which occurs some of the finest agricultural land in this country, consists of blue-grey clays and shales, often calcareous. The limestones are detrital, the result of denudation of older limestones, and were deposited near the shore. Ironstones are common and the clay and limestone mixtures produce cements. The limestones are generally below with the clays above. The ironstones of the north, in Lincolnshire and Cleveland, are very important. They are of iron carbonate and silicate which weather to limonite.

The Lias is followed by the Middle Jurassic with the Lower Oolites as the main members. These are shallow-water, current-bedded oolitic limestones in the south with clays which were deposited in deeper, more tranquil waters. The calcareous nature of the beds is reduced to the north and sands predominate with fresh-water deposits above. The Oolites are divided into two series, the Inferior Oolite below and the Great Oolite above. In Yorkshire the deposits are deltaic with sandstones, shales and thin coal seams and at Brora in Sutherland the thin coal seams have been worked for local supply. The beds of the Lower Oolites are of a variable and inconsistent character.

Above comes a series of clays of the Upper Jurassic with shelly and coral limestones and sands. The bottom series, the Oxford clay, is very uniform and consists of a bluish clay on which is founded an important brick-making industry in the Peterborough district. The next series, the Corallian, is variable and consists of shelly, oolitic or coral limestones with clay bands in the south but, to the north, the clays predominate except in North Yorkshire where limestones are again important. The Kimmeridge Clay is next in the succession. This also is very uniform and a dark grey or black shaly clay reaching a thickness of 400 yd in Oxfordshire. Above this comes the Portlandian limestones, including the Portland Building Stone, and yellow sands and then the Purbeckian consisting of shales, marls and limestones with gypsum beds.

The Cretaceous

Although sedimentation was continuous during the Jurassic and the succeeding period, the Cretaceous, and there is no unconformity between the two systems in South Lincolnshire and Sussex, elsewhere there is unconformity with overlap, the break increasing to the W. and NW.

The Cretaceous rocks of this country are exposed in a broad band from Dorset to Flamborough Head where they have a S. or a SE.

inclination, with a band running off eastwards along Salisbury Plain to the coast and a narrow strip bordering the Hampshire Basin in the Isles of Purbeck and Wight.

The escarpment of the Upper, dominant portion of the system, the Chalk, is to the west overlooking Jurassic or Triassic plains and sinking under Tertiary or recent deposits eastwards. The system is divided into two portions—the Lower Cretaceous consisting of sands and clays and the Upper of Chalk. The transgression of the Chalk Sea westwards in Upper Cretaceous times (when practically the whole of the British Isles must have been covered, since patches of Upper Cretaceous occur on the borders of the Antrim basaltic plateau and below Tertiary basalts in Mull and Morven), overlapped most of the Lower Cretaceous which is exposed only in the north and south, and in addition, the central portion was land until almost the end of the Lower Cretaceous (Fig. 89).

The Chalk consists mainly of comminuted shell fragments with some Foraminifera and microscopic calcareous algae, laid down in clear water which may indicate arid conditions in the lands bordering the Chalk. The depth would not be greater than 600 fathoms and probably much less. Sponge spicules and layers of flint are associated with the Chalk and the Lower Cretaceous flora is distinctive in the initial appearance of flower-bearing plants—Angiosperms. Reptiles are common including *Iguanodon*. As already mentioned the lower divisions of the Lower Cretaceous were only deposited in the south and north and the type of deposit in the two areas is entirely different.

In the southern, Weald area, the lower division, the Wealden, was laid down in fresh-water conditions in a lagoonal or lacustrine area. The succession and type of sediment is indicated in the following table in descending order—

Lower Cretaceous	Lower Greensand—a variable series of sands and clays, often calcareous, the sands sometimes suitable for glass-making	
	Wealden	Weald Clay—yellow, brown or blue clay with shelly limestones
		Hastings Sand—consisting of sands and soft sandstones with a clay band in the middle with formerly important ironstones

The Lower Greensand is marine and coloured by glauconite. It is present in the central portion and marks the breakthrough of the sea into the fresh-water area of the Weald. In the north, Yorkshire and Lincolnshire, the deposits corresponding to the Wealden and the Lower Greensand are all marine and consist of dark clays or shales

in Yorkshire and sandstones and limestones in Lincolnshire. The most important fossils are the Belemnites which are utilized for zoning (Fig. 90).

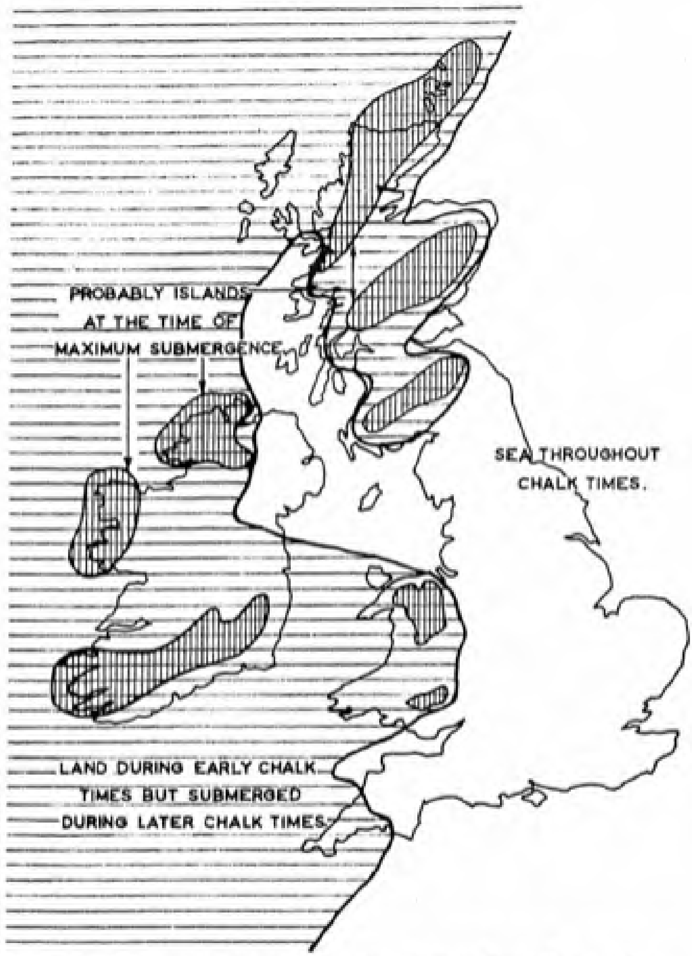


FIG. 89. DISTRIBUTION OF LAND AND SEA IN CHALK TIMES AND WESTWARD TRANSGRESSION OF CHALK SEA

The Upper Cretaceous which accompanied the transgression of the Chalk Sea to the west, which occurred not only in the vicinity of the British Isles but on a world-wide scale so that the relative proportion of land to sea was considerably reduced, is entirely marine and is

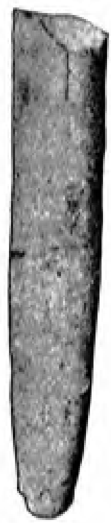
divided into a lower argillaceous and arenaceous, clays and sands, portion and a calcareous, chalk, upper portion.

The succession in descending order is—

Upper Cretaceous	Upper Chalk—attaining 1,150 ft in thickness with flint layers
	Middle Chalk—with marl beds and few flints
	Lower Chalk—often grey at base and without flints
	Gault and Upper Greensand—consisting of clays and sands

The Chalk is, of course, very porous and has been the source rock, with the impermeable Gault beneath, of London's former water

FIG. 90. A CHALK BELEMNITE.
Belemnites mucronata (SCHLOTHEIN)
From the Upper Chalk; about natural size.



supply. The water-table has been lowered hundreds of feet during the past century and only a small fraction of the supply now comes from this source. Danger of pollution has also been increased.

The Tertiary

The dividing line between the Mesozoic and Tertiary eras occurs at the summit of the Upper Chalk, denuded away or never deposited in this country although well developed in Denmark, so that the Tertiary rests unconformably on the eroded surface of the Chalk. This era is differentiated by an increasing preponderance of living genera of fauna and flora. The change was somewhat abrupt as the Cretaceous ended in an uplift which destroyed the Chalk Sea and

replaced its clear waters by the muddy waters from a great river running eastwards with consequent change of fauna including the appearance of placental mammals.

The exposure of Tertiary rocks is very limited in the British Isles and the middle series, the Miocene, marked by great mountain-building tectonic movement, is not represented in this country, but Tertiary beds reach thicknesses of tens of thousands of feet in Asia. The orogenic movements in early Tertiary times were world-wide and resulted in the formation not only of the Alps but also of the Himalayas, Andes and Rocky Mountains. Although the effects were much subdued in the British Isles, plateau basalts were extruded in Antrim and in Skye, Rum, Mull and Ardnarmurchan on the west coast of Scotland accompanied by swarms of dykes one of which, attaining 80 ft in width, the Cleveland Dyke from Mull, extends almost to the east coast at Whitby.

In the Miocene period uplift occurred producing a monocline with a westerly axis running through the Isle of Wight and the anticline of the Weald. The northern land-mass, present with a fluctuating shore-line since Cambrian times, was engulfed at this period.

The Tertiary rocks have been divided as follows, in descending order—

Upper Tertiary	Pliocene—Crags and Cromer Forest Series
	Miocene—absent
Lower Tertiary	Oligocene—Isle of Wight limestones and marls
	Eocene—Bagshot Sands, London Clay and Thanet Sands

The Eocene, exposed on each side of the Weald anticline in the London and the Hampshire basins, consists of sands, clays and pebble beds laid down in a shallow sea. To the west the beds become estuarine. The Thanet Sands at the base are light-coloured sands above which comes the bluish-grey London Clay, 400–500 ft in thickness, becoming sandy towards the top and passing up conformably into the Bagshot Beds above consisting of light-coloured sand with pebble beds, current-bedded. The beds above, the Bracklesham and Barton Beds, are more strongly developed in the Hampshire basin. These consist of sands, partly estuarine and partly marine.

The Oligocene occurs only in the Hampshire basin and represents a change from sea to land, the deposits consisting of brackish or fresh-water sediments including clays, marls and occasional limestones and lignites.

The Upper Tertiary is represented only by the Pliocene, the Miocene Period being represented by the folding already mentioned. The Pliocene was a period of submergence during which shelly sands and gravels were laid down in a shallow sea with much false-bedding,

represented by the different "crag" beds with the Cromer Forest-bed Series at the top. This consists of five beds with stumps of trees embedded in clay which have been drifted into their present position. The two top beds were formed under arctic conditions and are sometimes considered to be Pleistocene although the climatic conditions of the Pliocene were becoming colder, heralding the coming Ice Ages.

The Quaternary

The Pleistocene, Glacial and post-Glacial deposits, represent the products of Ice Ages and the genesis and development of man to the present day. The Ice-sheet spread over the British Isles, with the exception of the highest peaks, north of a line from the Bristol Channel to the Thames. The deposits consist of drift and Boulder Clay, the pebbles of which indicate the point of origin of the glaciers which conveyed them. The track of the glaciers is also marked by erratic boulders and perched rocks. River drainage was greatly modified and diverted, e.g. the Dee and the Severn, by ice blocks. The snow-fields were situated in Scandinavia, the Scottish Highlands, the Lake District and North Wales. The power of the glaciers as agents of transport is exemplified by passage over cols and necks well over 1,000 ft above sea level of pebbles of Shap Granite to Yorkshire.

Interglacial periods or period seems to have occurred in which warm water shells, animals of semi-tropical climates and primitive man established themselves. Changes of sea-level occurred, probably through the weight of the ice-sheets, with recovery when these melted indicated by submerged forests, peat beds and raised beaches.

The Post-glacial deposits are annotated by the remains, tools and ornaments of primitive man and his development in his successive cultures, Stone, Bronze and Iron ages. These begin the record of Pre-history leading to Historical times in which dates begin to have meaning.

QUESTIONS

1. Give some account of the New Red Sandstone system and indicate its importance to the coal mining engineer.
2. Describe the Jurassic system and mention the deposits of economic importance found in this system.
3. Give an account of the Cretaceous System.
4. Give some account of the type of deposits associated with the Tertiary and Quaternary eras.
5. What do you understand by the terms Permian and Old Red Sandstone? What is their significance in connection with coal mining?

CHAPTER IX

GEOLOGICAL MAPPING

AT every colliery an adequate supply of maps produced by the Geological Survey, based on the Ordnance Survey contoured maps of 1 in. or 6 in. to a mile, must be available. The Geological Survey map in commonest use is to a scale of 1 in. to the mile, but in coal-field areas 6 in. to the mile maps and in some complex areas maps on a scale of 25 in. to the mile should be available; maps on a scale of 6 in. to the mile, if available, must be provided at every mine, showing superficial and drift deposits; Mines and Quarries Act, 1954, Sect. 21, and Sect. 10 of the Coal and Other Mines (Surveyors and Plans) Regulations, 1956.

On a smaller scale, being useful where a region of considerable extent is to be studied, is the $\frac{1}{4}$ in. to a mile Geological Survey map. All students should procure a copy of that for the region in which they live and also that of the British Isles, to a scale of 25 miles to an inch. The latter is invaluable in following the exposures of geological systems referred to in the preceding chapters. Regional Handbooks and District Memoirs, if available, should also be consulted with reference to the district or region concerned.

Geological maps are of two types—"solid" and "drift" editions (Fig. 91). In the former the mantle of vegetation, soil and superficial deposits, except river alluvium, is assumed to have been removed so that the geology of the solid rocks below is revealed. In the latter all superficial deposits are indicated—glacial drift, residual deposits, river-gravels and terraces—thus representing a faithful picture of the ground as it actually occurs and obscuring much of the solid geology below except where rocks project through the superficial deposits as crags, bare patches of rocks on hill-sides or are exposed by stream and river erosion.

Generally the "solid" edition is of greater utility to mining engineers but the "drift" edition is probably of greater use to civil engineers and others when surface structures are to be built and will indicate desirable sites where strata suitable for foundations are present at surface. It is also essential for safety where shallow deposits are mined.

When a geological map is used in the field it is necessary to orientate it with reference to important land marks on the area covered by the map or by compass bearing.

The indications on the map are those of the outcrop or locus of points at which a particular bedding plane or line of demarcation between two adjacent geological formations is at the same height above datum as the ground surface. The trace of the outcrop of a particular bedding plane will, therefore, depend upon the direction of strike and the inclination or dip of the bed and also upon the surface configuration as indicated by the contours on the map.

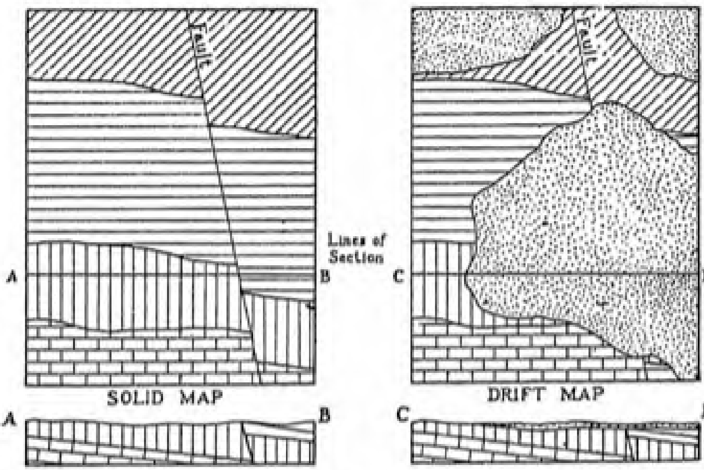


FIG. 91. GEOLOGICAL MAPS, "SOLID" AND "DRIFT" EDITIONS

Illustrating the difference between a Map showing the distribution of the Superficial "Drift" deposits, and a map of the same Area showing the "Solid" geology.

Thus if Fig. 92*a* represents an area whose configuration is indicated by the contours, consisting of two hills with a valley between, and Fig. 92*b* represents the height of the floor of a coal seam above Ordnance Datum at intervals of 100 ft (stratum contours), the seam dipping uniformly to the SE., the parallel lines are then the stratum contour lines or so-called strike lines for the floor of the seam. Superimposing one map over the other gives Fig. 92*c* in which the outcrop of the floor of the seam will be the thick line through the points *a*, *b*, *c*, *d*, *e*, *f* . . . , the points being those at which the stratum contours and the ground contours *for the same height above O.D.* coincide.

Conversely, it is possible from the shape of the outcrop to deduce the inclination of the bedding-plane of the floor of the seam, and so from a number of such crops to deduce the geological structure of the rocks beneath. It is evident that both surface topography and the inclination of the bed will affect the shape of the outcrop.

Horizontal strata will give crops parallel to the surface contours while vertical beds will give straight-line outcrops irrespective of the surface configuration. Between these two limits the direction of strike of the beds increases in influence on the shape of the outcrop

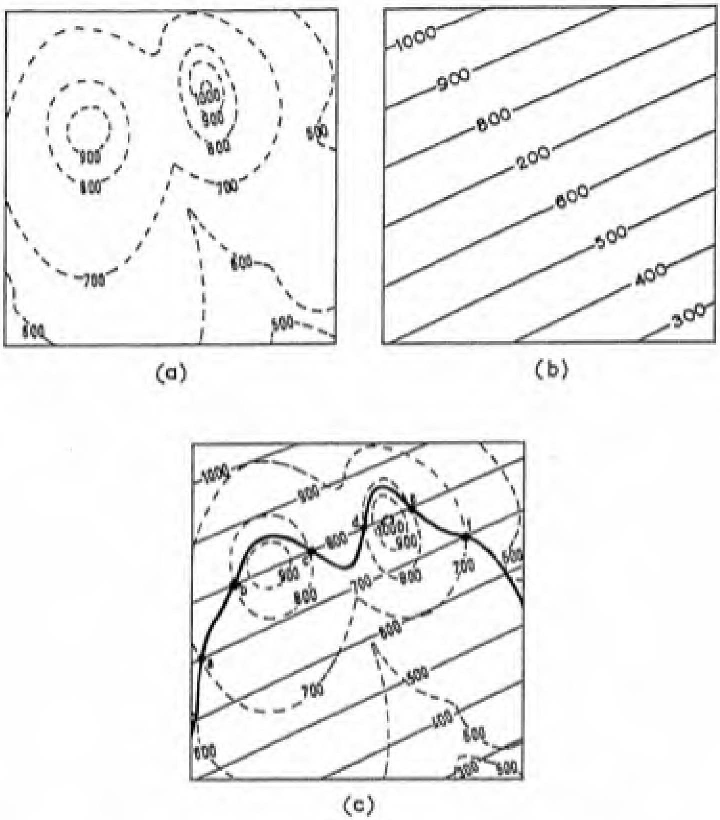


FIG. 92

as the inclination increases. Although the inclination and the direction of strike of bedded strata are not constant over large areas, locally they may be fairly constant and this is often the case in the area represented by the royalty or "take" of a colliery. Although the amount of inclination of a bed, true or apparent, is generally determined by means of some type of clinometer (Fig. 30), it may also be obtained from the depth of boreholes to a given stratum, for example, a coal seam, or from the height above or below datum

of points on a plan of colliery workings in a seam determined by levelling underground.

Thus in Fig. 93 three boreholes *A*, *B*, and *C* have penetrated the same coal seam at depths of 450, 675 and 550 ft respectively, the heights above O.D. of points *A*, *B* and *C* at surface being 250, 375 and 150 ft respectively. The levels of the seam below O.D. at *A*, *B* and *C* are respectively 200, 300 and 400 ft, the seam being deepest at point *C*. From *A* to *C* the seam falls 200 ft and from *B* to *C*, 100 ft. At point *D* midway along *AC* the seam will be 100 ft above *C*,

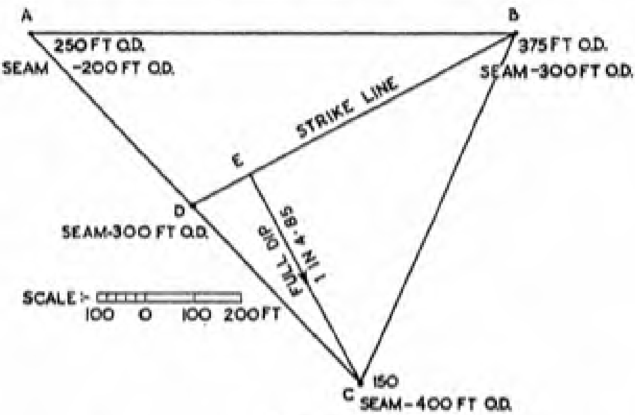


FIG. 93

therefore at *D* and *B* the seam is at the same level and *BD* is the direction of strike of the seam. If *CE* be drawn at right angles to *BD*, *EC* will be the direction of full dip and as *C* is 100 ft below *E* and *CE* measures 485 ft to scale then the rate of true dip is 100 in 485 ft or 1 in 4·85.

Similarly, in Fig. 94, *A*, *B* and *C* are three points in the workings of a coal seam, the levels of which are 227·50, 185·60 and 150·70 ft above O.D. The distance *AB* to scale is 970 ft, *AC* 954 ft and *BC* 440 ft, and *C* is again the lowest point of the three. From *A* to *C* the seam falls 76·80 ft and from *B* to *C* it falls 24·90 ft. A point *D* on *AC* will be 185·60 ft above O.D. or 24·90 ft above *C* when *CD* is $\frac{24{\cdot}90}{76{\cdot}80} \times AC$ ft or $\frac{24{\cdot}90}{76{\cdot}80} \times 954 = 309{\cdot}3$ ft. As *B* and *D* are again the same height above O.D. then *BA* is the direction of strike of the coal seam, N.56°E., and *EC*, at right angles to *BD* represents the direction of full dip, the rate of which is 24·90 ft in the length of *EC* = 270 ft or 1 in 10·84.

Where the workings in a seam are extensive and as these have to be levelled to conform with the requirements of the Coal and Other Mines (Working Plans) Rules, 1956, Sects. 4 and 5, it is often advantageous to plot the contours for the coal seam relative to Ordnance Datum, the interval between the contours depending on the rate of full dip of the seam, the steeper the dip the greater the interval between the contours. The information obtained in this manner is often of value in forecasting changes in inclination and strike and faulting which are likely to be encountered beyond the extent of the present workings. In difficult cases it

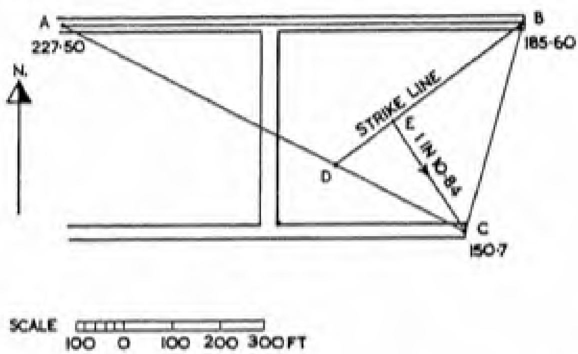


FIG. 94

may prove advantageous to model to scale in plaster of Paris the workings of one or more collieries in a particular seam. Such scale models are useful in mine-planning not only in the particular seam but also in seams open above or below it in the geological succession. Fig. 95 shows such a model of workings, faults and changes in the inclination of the Parkgate seam in the Sheffield area. In horizon mining schemes similar models are particularly useful.

For a bed of thickness t feet (Fig. 96), measured at right angles to the top and bottom bedding planes bounding the bed, the width of the outcrop on level ground w is $t/\text{sine } i$, where i is the true dip of the bed in degrees. If the ground also slopes the width of the outcrop will be increased or decreased according to whether the ground slopes in the direction of or contrary to the dip of the bed. Thus if $a°$ is the slope of the ground, the width of the outcrop w_1 where the slope is in the same direction as the dip is $\frac{t}{\text{sine }(i - a)}$; where the slope is contrary to the dip the width w_2 of the outcrop is $\frac{t}{\text{sine }(i + a)}$

FIG. 95. MODEL OF WORKINGS IN THE PARKGATE SEAM IN THE REGION OF THE DON FAULT (A MONOCLINE)

(Fig. 97). It is seldom possible to trace the complete outcrop of a bed in an area, but if the bed is dipping uniformly, the rate of dip and the bed contours may be constructed and the trace of the outcrop com-

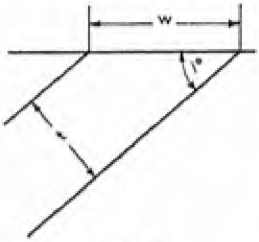


FIG. 96

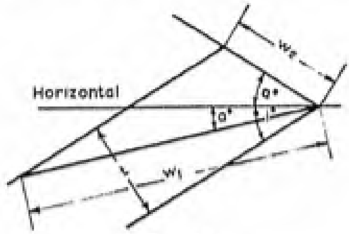


FIG. 97

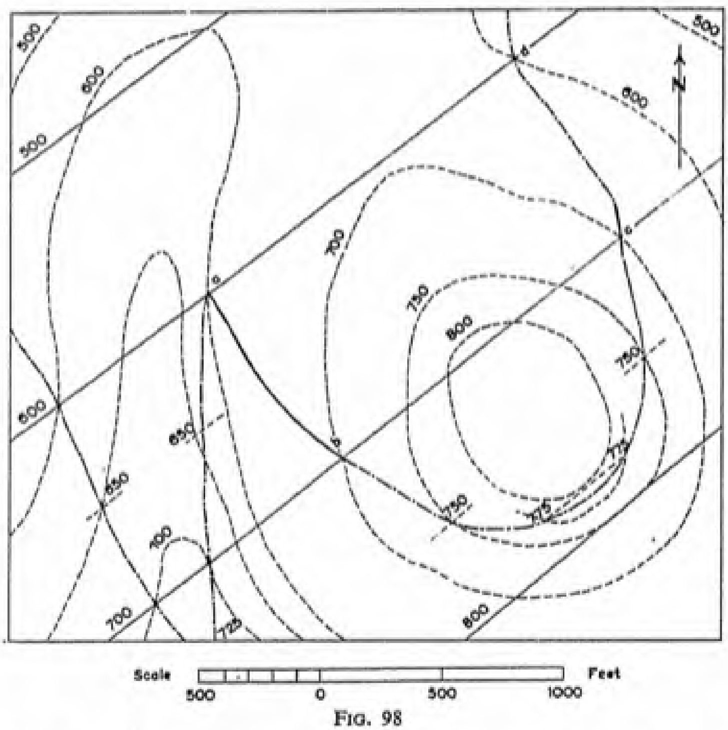


FIG. 98

pleted from the points of intersection of the bed contours with the ground contours of the same value. Thus in Fig. 98 *a*, *b* and *c* are portions of the outcrop of a coal seam. As *b* and *c* are points on the same ground contour, 700 ft, they may be joined and *bc* is a strike

line in the seam and is the seam contour for 700 ft. Parallel to *bc*, *ad* may be drawn through *a* and this will be a strike line and the seam contour for 600 ft. The distance apart of these seam contours gives the horizontal interval and seam contours for 500 ft and 800 ft may be drawn parallel to the first two. The continuation of the outcrop

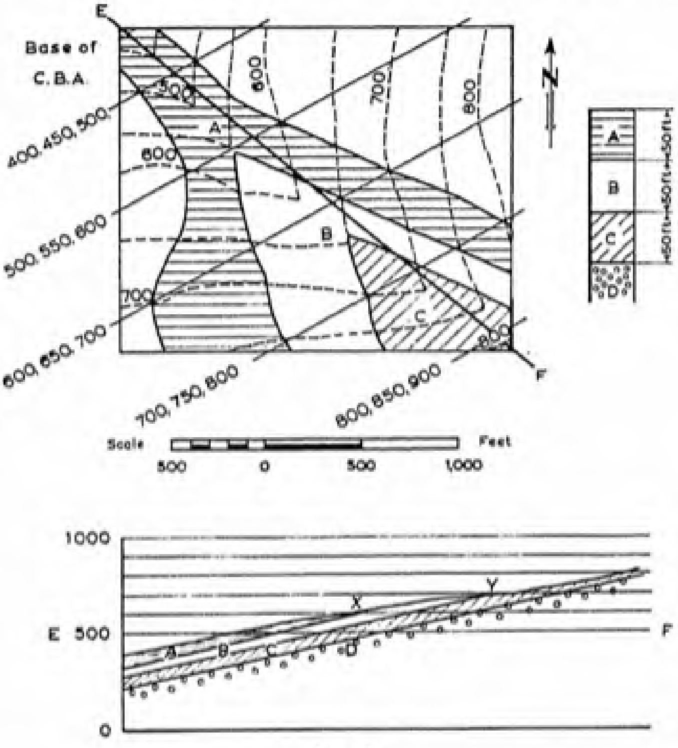


FIG. 99

can now be followed and is shown by a dot-and-dash line in Fig. 98, extrapolation for intermediate intervals of the strata and ground contours being used where required. The rate of full dip is 100 ft in the horizontal interval of 875 ft, or a dip of 1 in 8·75 in a direction N.38°W.

Outcrops and Thickness of Uniformly-Dipping Beds

Fig. 99 shows the outcrop of the bedding planes between three members *C*, *B* and *A* in ascending order of a group of uniformly-dipping strata. Bed contours for the bottom of bed *A*, for the

junction of beds *A* and *B* and for beds *B* and *C* are shown in succession from right to left on the side of the map and strike lines have been drawn across the map. Each strike line will represent 1 the bottom of bed *A*; 2 at a level 50 ft below for the junction of bed *A* and *B* and 3 at a level 50 ft further below for the junction of beds *B* and *C*.

In this case beds *B* and *C* are each 50 ft in thickness as can be determined by comparing the strike lines for the top and bottom of each bed. The rate of full dip is given by the horizontal interval to scale between the strike lines for any bed, divided by the vertical interval. In this case the horizontal interval is 500 ft and the vertical interval is 100 ft, so that the rate of full dip is 1 in 5 in a direction at right angles to the direction of the strike line, i.e. N.28°W.

In order to understand the geological structure of the area a geological section may be plotted from the outcrops in any required direction. To plot a section in the direction *EF* the straight edge of a piece of paper is placed along *EF* and on it are marked the contours of the ground and the points at which the bedding planes between the beds *A*, *B* and *C* respectively outcrop. From a base line heights are set off at intervals of 100 ft to the same scale as the horizontal distances. The cross-section is plotted as shown, the bedding planes being set out at each point of outcrop so that the geological structure beneath the surface along *EF* is revealed.

Unconformities

Previously beds or groups of beds of strata dipping uniformly in the same direction have been considered, that is the beds have been conformable. When new beds are deposited on the eroded surface of older beds an unconformity results and the two sets of beds generally have different directions of strike and different rates and directions of inclination. The two sets are separated by a plane of unconformity with an inclination and direction parallel to that of the dip of the newer beds but in actual practice, owing to erosion, the surface of unconformity is often uneven as a result of differential erosion of the older beds.

Fig. 100 is a geological map of a small area in which the rock succession consists of conformable beds *A*, *B*, *C*, *D* and *E* and an unconformable newer bed *X*. Strike lines are drawn at 100 ft intervals and for the beds *A* to *E*, which are conformable and of thicknesses shown by the enlarged section of strata on the right-hand side of the map, the same strike lines with different values serve for the junctions of each pair of beds. From these it is apparent that each bed falls 100 ft in the 500 ft distance between the strike lines

so that the true dip of the conformable series *A–E* is 1 in 5 in a direction S.46°E.

It is assumed that the plane of unconformity, which has been removed by subsequent erosion over a large proportion of the area,

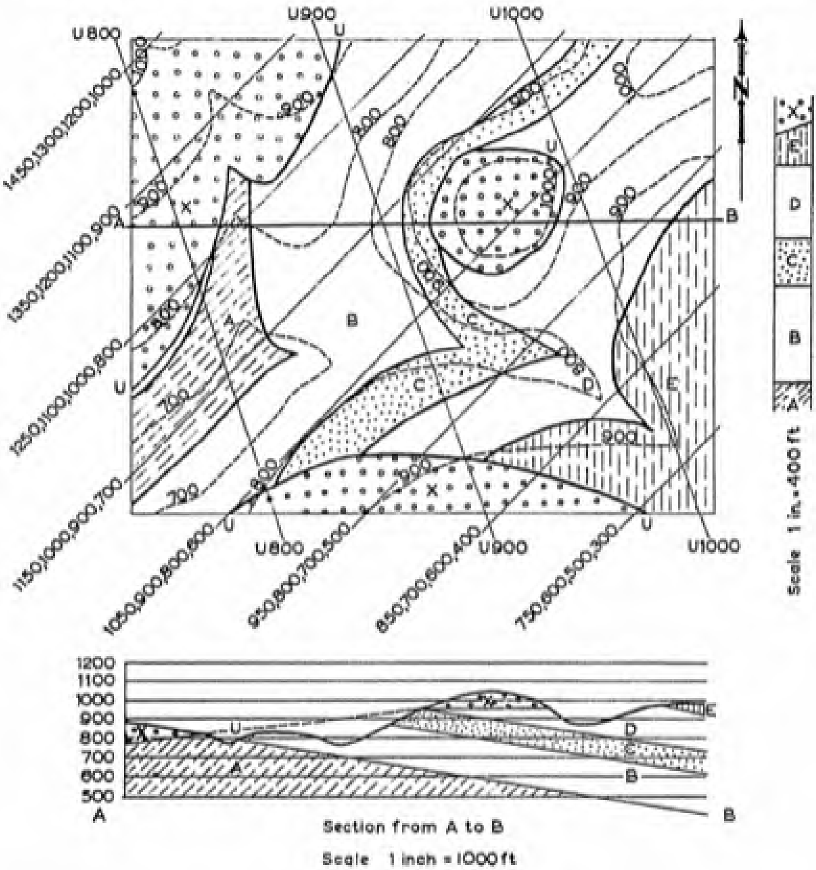


FIG. 100

was originally a plane surface parallel with the bedding planes of the series of strata above, of which only patches of the lowest bed *X* remain. Strike lines marked *U* are drawn for this plane of unconformity which has a full dip of 1 in 10·25 in a direction S.71°W. It will be noted that the plane of unconformity, which is also the base of bed *X*, transgresses successively different members of the older series: this is particularly apparent at the bottom of the map. This

transgression is the most evident indication of an unconformity in the field.

From the map, sections of strata may be constructed in any required direction. If a direction from A–B is chosen, a straight-edged strip of paper is laid with the edge along this line. The positions of the junctions between pairs of beds and of the contours as they cross AB are marked. The ground profile in the direction AB is now constructed by marking the points of intersection of the contours at the requisite heights on the section. To prevent exaggeration of dips it is preferable to use the same scale for both vertical heights and horizontal distances, in this case an inch to 500 ft for both. The points of intersection of the junctions of pairs of beds are now plotted on the profile in their correct position and height from the paper strip. The apparent dip of the beds of the older series in the direction of AB (W.–E.) is seen to be 1 in 7 to the east and this may be checked by the distance apart of the strike lines in this direction on the map. Similarly the apparent dip of the plane of unconformity and of the bed X is 1 in 10·65 to the west. The thicknesses of the beds A, E and X cannot be determined from information provided within the limits of the map but those of the other beds may be determined by drawing the strike lines for the bases of the respective beds and then those for the tops of the beds in the same position. The differences give the thicknesses and these are shown in the margin of Fig. 100.

Faulting

Fig. 101 shows an area with two rock successions, an older sequence A–E and an unconformable upper sequence X, Y and Z. The former is shown by constructing the necessary strike lines to dip NW. at 1 in 5 while the upper sequence dips due south at 1 in 10. Two faults F_1 and F_2 occur in the area, the latter affecting the lower sequence only and so was antecedent to the unconformity and the upper sequence but the fault F_1 displaces both sequences and so was later than the time of the deposition of the topmost bed exposed, Z.

Comparison of strike lines on either side of the faults indicates that F_1 has a downthrow to the NE. of 150 ft and is a dip fault, i.e. parallel to the direction of the full dip of the lower sequence, while F_2 is a strike fault throwing SE. 300 ft.

Sections across the map may be constructed as in the last example by marking on the edge of a straight strip of paper the intersections of the beds at outcrop and the contours. If the direction AB is chosen the cross-section shown results, the older sequence having an apparent dip of 1 in 7·07 due west and the upper sequence a direction

of strike due west. As the outcrops of the fault planes are shown as straight lines unaffected by surface configuration then they must be vertical and are so drawn on the cross-section. Usually normal

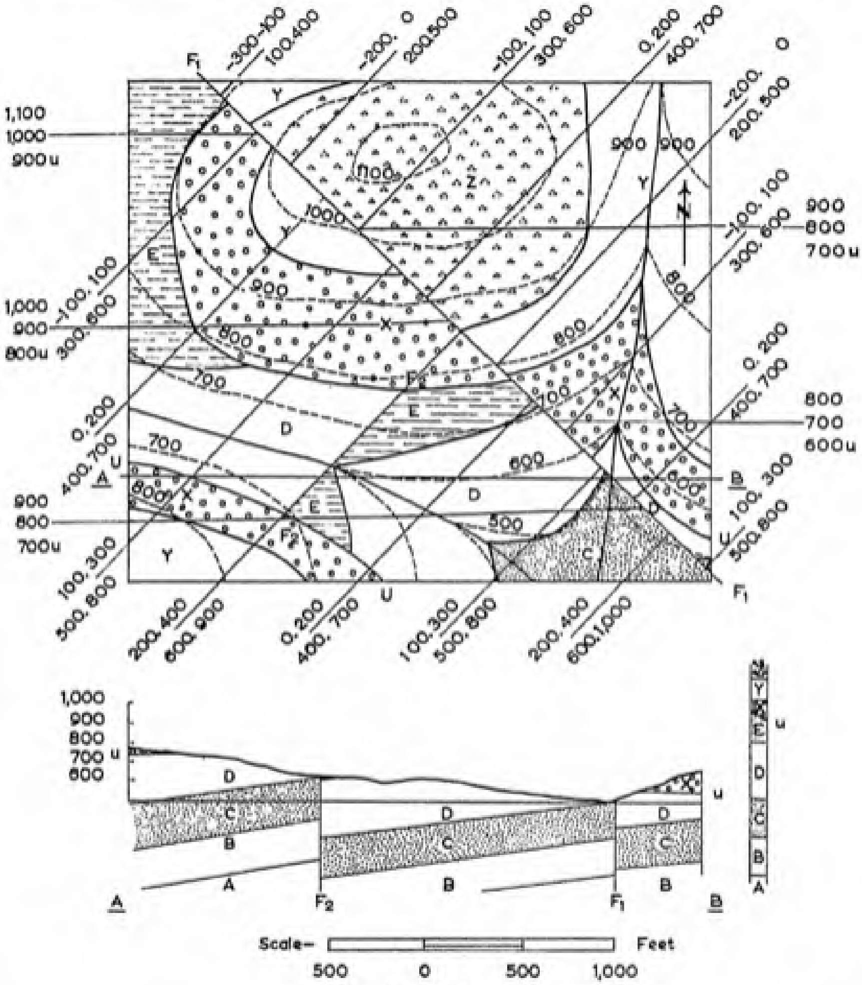


Fig. 101

faults of this type have a fairly high hade, the angle to the horizontal being commonly about 70°. When the fault plane, like a surface of unconformity, has a dip and strike its outcrop is slightly curved and depends on the configuration of the ground.

Folding

In the previous examples the strata has been assumed to dip uniformly but this is rarely the case over long distances and intense folding may occur in a particular area. It is clear that when the

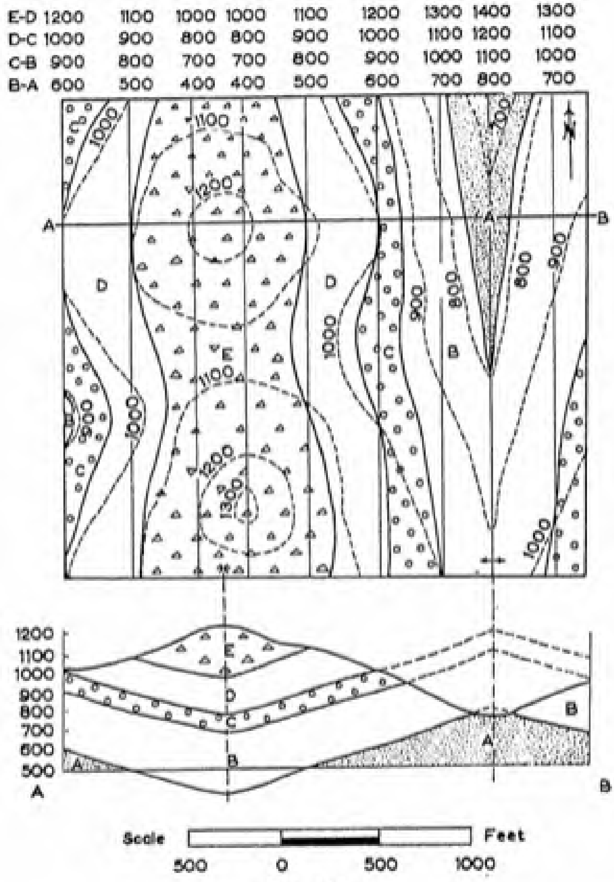


FIG. 102

rate of dip alters due to folding, the strike lines will not remain a constant distance apart. This is illustrated in Fig. 102 which shows symmetrical and asymmetrical folding of five beds *A–E* into a syncline followed by an anticline, the axes of the folds in this case being horizontal. The strike of beds is N. and S. The syncline on the west is symmetrical and the succeeding anticline is asymmetrical,

that is the western limb is steeper than the eastern limb. The strata contours show that the rate of full dip W. – E. of the map are respectively 1 in 3·75 to the east, 1 in 3·25 to the east, turn-up of the fold, 1 in 3·25 to the west, 1 in 3·75 to the west, 1 in 3·25 to the west, 1 in 2·5 to the west and finally 1 in 3·25 to the east.

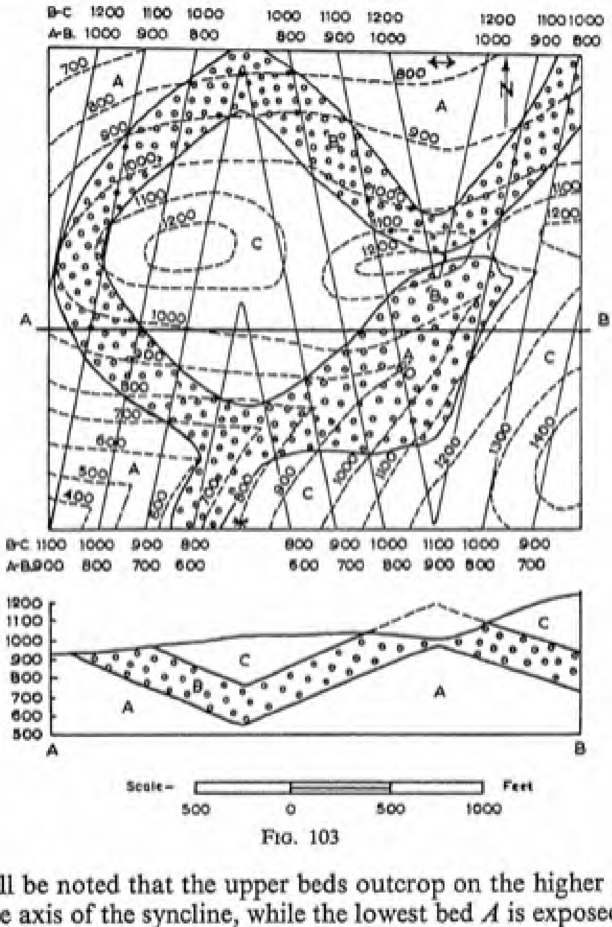


FIG. 103

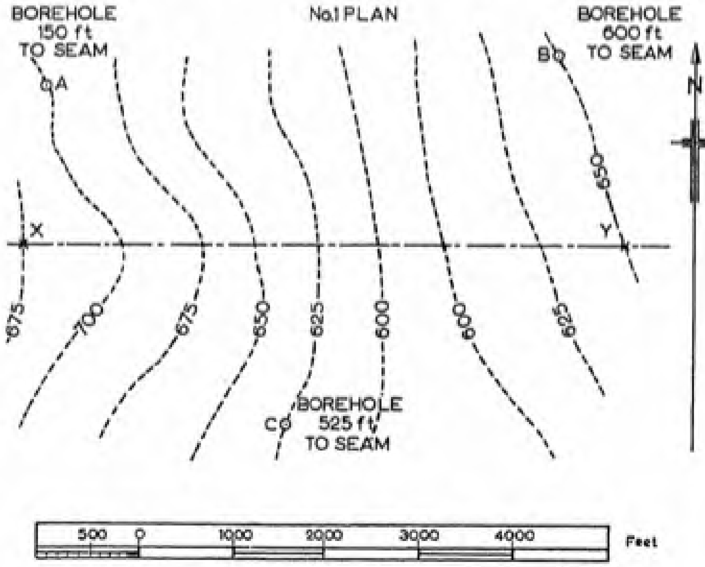
It will be noted that the upper beds outcrop on the higher ground near the axis of the syncline, while the lowest bed *A* is exposed in the river valley on the axis of the anticline. Cross-sections across the area indicating the structure may be constructed which will show the folding. Such a section from W. – E. at *AB* has been constructed by marking contours and outcrops on a straight-edged strip of paper and thicknesses of beds and depths above O.D. projected down on the section from the stratum contours.

In Fig. 103 the folds are symmetrical but are pitching due south with a pitch of 1 in 12·5. The beds of the western limb of the syncline dip at 1 in 2·4 in a direction S.78°E., in the eastern limb of the syncline and in the western limb of the adjacent anticline they dip at 1 in 2·4, S.78°W. and finally they dip 1 in 2·4 in a direction S.78°E. in the eastern limb of the anticline. The stratum contours for the junctions of the beds *A*, *B* and *C* are shown on the upper and lower margins of the map. It will be noticed that the oldest bed *A* is exposed in the NW., NE. and SW. corners of the map and also has a very small exposure in the middle of the outcrop of the bed above, *B*, SE. of the centre of the area. By marking on a straight-edged piece of paper a cross-section may be constructed to indicate the geological structure. This has been carried out for the direction *AB* west to east across the area in Fig. 103. The apparent dip of the beds in this direction is 1 in 2·5 east and west respectively.

QUESTIONS

1. Describe the two types of geological map available to the mining engineer.
2. The No. 1 plan below shows surface contours with level values in feet above Ordnance Datum, positions of three boreholes *A*, *B* and *C* and the depth from the surface to No. 1 seam at each borehole.

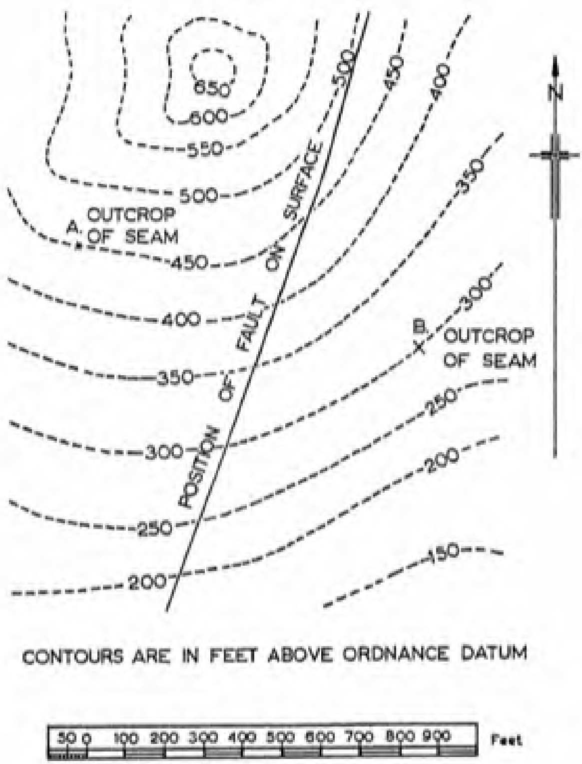
Assume that the depth of the seam is uniform and that there are no faults.



Determine by a graphical method bearing and full dip of the seam and plot a section along the line XY to a scale of 6 in. = 1 mile for horizontals and 1 in. = 200 ft for verticals, showing the profile of the surface and the position of the seam.

3. The No. 2 plan below shows surface contours in feet above Ordnance

No.2 PLAN



CONTOURS ARE IN FEET ABOVE ORDNANCE DATUM

Datum, points A and B where a seam outcrops and the position of a fault at the surface.

The dip of the seam on each side of the fault is 1 in $2\frac{1}{2}$ in a direction due South.

Draw on the plan the outcrop of the seam on each side of the fault and mark on the fault an arrow indicating the direction of throw.

4. Show by a diagram how an unconformity would be revealed by a geological map.

5. Illustrate by means of a diagram how faulting can be discovered by the use of a geological map.

6. Show by means of a diagram how folding can be discovered by the use of a geological map.

CHAPTER X

MINERAL DEPOSITS OF ECONOMIC IMPORTANCE

In addition to coal the principal substances obtained by some method of mining and quarrying are the ores of metals, building and road materials, salt, gems, abrasives and phosphates and nitrates for the chemical industries. Broadly speaking these materials may be said to occur in two ways; as tabular deposits including beds and veins or as non-tabular occurrences generically known as "masses."

BEDS OR SEAMS

A "bed" or a "seam" is some special number of a series of stratified rocks deposited by one of the methods by which such deposits are laid down which, by reason of its lithological composition or the concentration of certain minerals in it, has a value in commerce. The bed may vary considerably in thickness, become unworkable at a profit by reason of the occurrence of valueless partings or gradual change in lithological composition but generally speaking it is more uniform both in workable thickness and in composition than a vein.

Many of the most important mineral deposits are beds containing a very small proportion of some metal but representing nevertheless an unusual concentration of that element elsewhere widely dispersed with a very low concentration; thus gold with an average concentration in surface rocks of 1 in 100,000,000 becomes a commercial proposition when its local concentration reaches 1 in 100,000. Similarly copper with a dispersed concentration of 1 in 10,000 becomes a paying proposition at $\frac{3}{4}$ per cent. On the other hand iron needs a concentration over 18 per cent to be worthwhile. For materials of low market value, like building and roadstone and limestone, practically the whole bed, which must have considerable thickness, must be saleable and the waste material or overburden, which must be removed to exploit the commercial stone, is strictly limited, although these limits have been extended with the introduction of mechanized methods of material removal such as mechanical shovels, draglines and scrapers.

Building and Road Stone

The main requisites of a building stone are durability and strength. Generally a medium-grained rather than a coarse-grained rock is to be preferred if alternative supplies are available. For wall stones and

flags a flaggy sandstone with well-marked bedding is required, while for ashlar freedom from jointing (freestone) is desirable. Artificial stone and concrete have replaced building stone for a number of purposes, such as roadway kerb, and this has increased the demand for sands and gravels and for crushed stone.

For road metal compactness, resistance to abrasive wear and good weathering properties are required and, particularly, ability to bind well with tars and other oil-residues to give the macadamized surfaces of modern motorways. Igneous rocks such as dolorite, diorite and gabbro are the most popular. Limestone is also used particularly as such roads dry quickly but the chief uses of this material are as a flux in iron-smelting and for the production of lime for agriculture and building.

Metamorphosed shales in the form of thin slates are the best possible roofing material for buildings but many local fine-grained flagstones are used for the same purpose. Artificial tiles are best considered with bricks as their mode of manufacture is similar.

Brick Clays

Clay, the ultimate product of the weathering of igneous rocks, consists mainly of hydrated aluminium silicates, and for building bricks, alkaline fluxes in small quantities are also required to form a silicate glass to bind the particles together at a relatively low temperature. Shrinkage in drying must not be excessive and may be counteracted by the addition of burnt material ("grog") to the clay when it is mixed.

The bricks may be moulded or wire-cut from a clay column forced through a die by a mechanically driven worm (pug). The bricks are then dried, in the older hand-worked yards by exposure to the atmosphere but in modern yards in drying corridors steam heated or heated by waste gases from the kilns. Kilns differ widely in details of construction and operation, they are intermittently or continuously fired, the fire passing from chamber to chamber round the kiln continuously. In tunnel kilns the bricks are loaded on to cars which are moved very slowly through a furnace.

The clay often contains carbonaceous matter which reduces fuel consumption as in the Oxford clays which contain bituminous "knots." These clays are used in the production of very large outputs of so-called "Fletton" bricks, the plants being highly mechanized. Coal Measure shales are extensively used for brick making and the carbonaceous matter they contain economizes in fuel consumption but the amount must be constant or the burning of the bricks cannot be controlled and wastage becomes high.

Below certain coal seams non-alkaline fire-clays occur which have refractory properties and are used in the manufacture of fire bricks. Ganister, which has a silica content of over 90 per cent, is used for making the highest grade of refractory bricks and furnace linings, as also is magnesia. For ceramic ware china clay from disintegrated weathered granite is used although ordinary clays may be used in the manufacture of drain pipes and coarse earthenware. Bauxite, $Al_2 O_3$, is the commonest source of aluminium and the availability of a sufficient supply of electricity for electric furnaces is a necessity. Hydro-electric stations have been erected with this object as their primary purpose.

Ore Deposits

An ore is a mineral or rock containing one or an aggregate of minerals capable of being mined at a profit and although particularly important in connection with the supply of metals also includes non-metals. The ores include deposits formed in a number of different ways, some of which are still the subject of discussion, varying from chemical precipitation or desiccation, and occurring as a special type of sedimentary rock, to solidification or crystallization as part of an igneous rock.

They may first be divided broadly into primary and secondary deposits, the former being those in which the mineral deposits have been formed in the positions in which they are now exploited, whereas the latter are those in which the minerals have been transported by some means to their present position from their place of origin.

The primary ore deposits have been sub-divided into—

1. Magmatic, produced directly by crystallization and segregation from an igneous magma and retaining an obvious correlation with the parent magma.

2. Pneumatolytic, produced by gaseous emanations at high temperatures which react with the cooled margin of the igneous mass and with the heated rocks into which the magma has been intruded, known in metal mining as the "country" rock.

3. Hydrothermal, produced by ascending solutions of high, intermediate or low temperature rising from a cooling igneous rock.

The secondary ore deposits may be subdivided into—

(*a*) Supergene, those precipitated from surface water percolating downwards or by desiccation of surface waters.

(*b*) Residual and detrital—produced by the removal of soluble material by denudation or the gravity sorting of sediments by water action.

Primary Ore Deposits

MAGMATIC

In order to achieve the necessary concentration of a mineral of economic value in a cooling magma some process of differentiation must take place. Broadly speaking the constituents of an igneous magma separate in a definite order and of the ore minerals some separate early (at high temperature). Among these are nickel, chromium and platinum, while the others crystallize late (at lower temperatures) since these, like lead, tin and zinc form more volatile compounds. The cause of segregation due to differentiation may be one of the following—

1. Immiscibility of the constituents of a molten igneous magma, particularly sulphides and silicates, in the same way that oil and water and molten iron and slag are immiscible and separate into distinct layers.
2. Sinking under gravity of the heavier, basic crystals, which form first, through the still molten remainder of the magma producing gravity segregation.
3. Crystallization taking place at the cooling boundary of the magma, the crystals being fed by convection currents diffusing to the margin to make good the reduced concentration of that particular constituent in the liquid there.
4. Filtration differentiation of the lowest freezing-point minerals, through the squeezing of these due to pressure from earth movement, through the crystalline mesh of the minerals of higher freezing-point which have already crystallized out.
5. Overhead magmatic stoping by the magma, fusing and assimilating the country rock into which it is intruded.

The iron-ores of Scandinavia, the platinum of the Urals and the diamonds of the Kimberlite or blue ground, an ultra-basic igneous rock rich in magnesia, of South Africa and other parts of the world are of the magmatic type.

PNEUMATOLYTIC AND HYDROTHERMAL

From the cooling magma emanations ascend which are gaseous if the temperature is high enough or hydrothermal if lower. The two types are, therefore, closely related. They consist of water, always in gaseous form whatever the pressure above 365°C, fluorine, chlorine, boron, sulphur and phosphorus which accompany the late stage in the cooling of a magma, particularly acid magmas like granite. These cause secondary changes in the minerals already formed and in the country rock resulting in the formation of a

characteristic suite of minerals giving useful indication to the prospector and including tourmaline, topaz and fluorspar together with quartz and calcite. Cassiterite (tin oxide) occurs in this manner in Cornwall. Wolframite, the ore of tungsten, occurs in the same way and Kaolin (china clay) results from the decomposition of felspar. Hydrothermal deposits, produced by the reaction of ascending solutions, represent the final stages in the intrusion of an igneous magma.

These solutions may find their way great distances from their parent source but eventually they deposit their dissolved minerals in

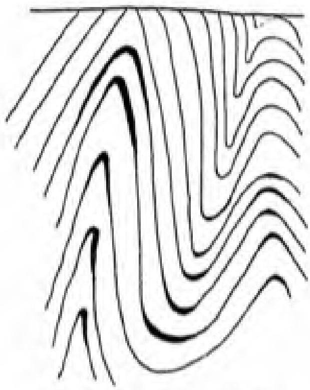


FIG. 104. SADDLE REEFS

cavities, fissures, fault planes and between the grains of porous and crushed sedimentary rocks. They have been divided into three types, the first being the high-temperature deposits which occur in the zone of altered country rock, or metamorphic aureole, round the magma. The ores which occur in this zone are sulphides of iron (pyrite), lead (galena), and zinc (blende), which are often found together. The Broken Hill, South Australia, British Columbian and many Canadian deposits are of this type. Copper, bismuth, antimony and arsenic with gold and silver also occur in this zone.

The next, or intermediate, temperature zone has a less deep-seated origin than the previous zone and is associated with igneous rocks of the hypabyssal and volcanic types. The minerals commonly associated with this zone are quartz, calcite and barytes and the ores are those of copper, lead and zinc, the former associated with gold and the latter with silver. The gold saddle reefs of Bendigo (Fig. 104) and the silver-lead deposits of Colorado are of this type.

The last, or low-temperature zone generally occurs at shallow

depths. The minerals, deposited in fissures and cavities and known as veins, exhibit a symmetrical structure with bands of crystals of different minerals on each side of the fissure (Fig. 105). Lead and zinc occur in this zone in narrow veins in joints and cavities in limestone in Derbyshire, Durham and Cumberland along with fluorspar and barytes. It would appear that hydrothermal emanations can carry more lead in solution than zinc when the distance from the parent magma is considerable, and in the deposits previously mentioned the connection with the parent igneous rock is remote and has

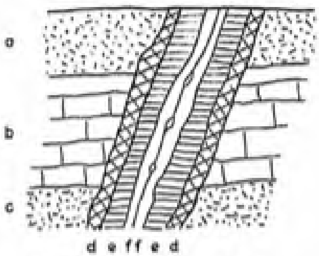


FIG. 105. VEIN IN LOWER CARBONIFEROUS
(*a*) Sandstone, (*b*) Limestone, (*c*) Sandstone, (*d*) Calcite, (*e*) Zincblende, (*f*) Galena.

yet to be established. Mercury, antimony, silver and gold also occur in this zone.

SECONDARY ENRICHMENT

Many mineral ores occur as sulphides and when exposed to the weathering action of percolating rain water, with dissolved oxygen and carbon dioxide, reaction takes place. Ground water finds its way downwards through the rocks to the water-table and between this level and the surface oxidation and carbonation proceeds and the sulphides are converted to sulphates, carbonates, oxides and hydroxides. These are often soluble and descend leaving a weathered "gossan" from which the sulphides have been removed. The descending solutions encounter reducing conditions at and below the water-table and are again precipitated as secondary sulphides or as native metals.

This zone is known as that of secondary enrichment in which the original mineral content may be greatly appreciated by the accession of this secondary material. Such an example is that of chalcopyrite ($CuFeS_2$). This is oxidized to copper sulphate and carbonate and insoluble iron hydroxide. The sulphates descend and react with pyrite, FeS_2 and the chalcopyrite to produce cuprous and cupric

sulphides in the secondary enrichment zone. The reactions may be of the form—

$$2CuFeS_2 + 7O_2 + CO_2 + 3H_2O = CuCO_3 + CuSO_4 + Fe_2(OH)_6 + 3SO_2$$

$$2CuSO_4 + 2FeS_2 = Cu_2S + 2FeSO_4 + 3S$$

$$CuSO_4 + CuFeS_2 = 2CuS + FeSO_4$$

Silver and gold in workable concentrations also occur in zones of secondary enrichment or "bonanzas" below a low grade primary ore in which the concentration is below the pay limit.

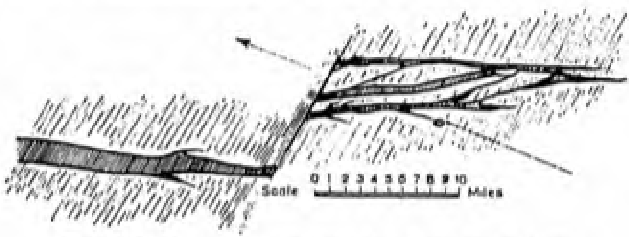


FIG. 106. FAULT INTERSECTING AND DISPLACING VEIN

MINERAL VEINS

The tabular bodies of minerals in which ores occur are known as "veins" or "lodes." They often occupy fault planes or fissures and may be dislocated or shifted by other faults intersecting them (Fig. 106). Veins, like faults, often occur in two sets at right angles and branches or offshoots from the main veins are common. The infilling of the fissures and cavities in the country rock is by igneous intrusion, by pneumatolysis, by deposition from hydrothermal solutions or from solutions at ordinary temperatures.

This is very apparent in the vein shown in Fig. 105 from the Lower Carboniferous in which *a*, *b* and *c* represent beds of sandstone and limestone traversed by bands of calcite, *d*, zinc blende, *e* and galena, *f*. This vein has been formed by successive approximately symmetrical layers on each side of the fissure or crack, demonstrating that the order of deposition of the different constituents is definite. Subsequent earth movement may cause re-opening of the fissure and further layers of other minerals may be added to the original vein. Pieces of the country rock may become detached as at *h* (Fig. 107), and become incorporated in the vein. These are known as "horses." In addition to these sharply defined veins in which the infilling material, valuable ores *e* and *f* and "gangue" or "veinstuff" *d*, the

valueless portion, in Fig. 105, ends off sharply at the sides of the original fissure, there are others in which the valuable constituent gradually fades into the surrounding country rocks from the fissure or "leader" *a* (Fig. 108).

Instead of a single fissure or clift there may be a group of several fissures more or less intersecting one another and the term vein is then applied to the whole of the sheetlike body of fissure material impregnated with some valuable ore. The vein may be a body of fault breccia or fault conglomerate cemented by minerals which have

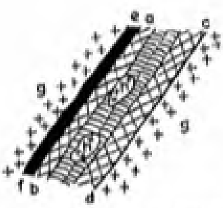


FIG. 107. VEIN WITH "HORSES"

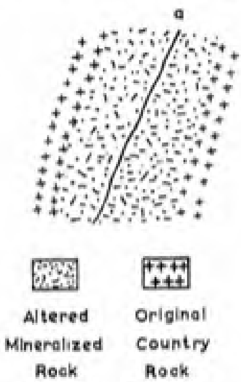


FIG. 108. WIDE VEIN WITH VALUES FADING INTO COUNTRY ROCK

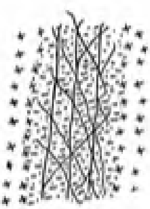


FIG. 109. STOCKWORK

been deposited in the interspaces which originally existed between the fragments and in the cracks which traversed them. Such an arrangement of veins and offshoots or "stringers" is sometimes distinguished as a "stockwork" and is shown in Fig. 109.

Although most deposits were obviously formed later than the country rock in which they are found the particular mode of formation is frequently difficult to disentangle and in some cases it is even difficult to decide with certainty whether the deposit was formed contemporaneously or subsequently to the country rock. For instance in some of the gold-bearing conglomerates, "bankets," of the Rand the gold was deposited contemporaneously with the pebbles on a Pre-Cambrian shore and is thus a very old "placer" or supergene deposit due to gravity water-sorting, but in the majority of cases the gold has been deposited from hydrothermal solutions.

Like a bed, a vein has dip and strike and as the dip is high, as with the hade of a normal fault, it is sometimes measured in degrees from the vertical and is then known as the "underlie," "underlay" or

"hade." The boundary planes of a vein are called the "walls" or "cheeks" and are frequently fault planes, their smoothed and striated appearance affording evidence of movement, and the two walls, through dislocation, may be of different rocks.

The wall above a vein is called the "hanging wall," *ab* (Fig. 107), and the one beneath, *cd*, the "foot wall." As with faults it is not unusual to find a layer of clay, *ef*, between the lode and the enclosing rock and this layer is called "a selvage," "dig" or "gouge." The country rock is lettered *g* in Fig. 107.

Veins are of less uniform productiveness than beds and are rarely worth working throughout. Rich portions alternate with poorer or worthless portions. Experience indicates that many conditions affect the productiveness of mineral veins, especially intersections with other veins and changes in the nature of country rock. In the Alston district of Cumberland for example, the lead veins are generally more productive in limestone than they are in sandstone or shales. Veins are often discovered in joint and bedding planes in limestone (Fig. 110), and in cavities at the tops of anticlines and the bottoms of synclines, the saddle gold reefs of Bendigo (Fig. 104), being a notable example. They are similar to those igneous intrusions known as "phacoliths."

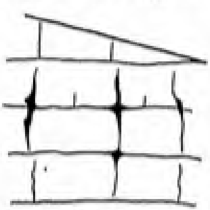


FIG. 110. GASH VEINS

Secondary Ore Deposits

SUPERGENE

Some of these deposits, the limestones and the ironstones, have already been mentioned and it remains to note those others which have been precipitated or crystallized out by supersaturation brought about by evaporation or by local chemical reaction. The products then take their place as normal sedimentary rocks, and being soluble, their preservation is often dependent on being covered quickly by an impervious bed of clay. The order of crystallization of soluble products in a land-locked sea or one with a bar which renders ingress easy but egress difficult or impossible, in the semi-arid conditions which characterized Permian and Triassic times in this country, is iron hydroxide, carbonates of lime and magnesia, followed by alkaline sulphites with gypsum or anhydrite ($CaSO_4$), at 37 per cent evaporation. Saturation for rock salt (NaCl), occurs at 93 per cent while the magnesium and potassium salts do not crystallize out until 98 per cent of the water has been evaporated. The Stassfurt deposits of Germany exhibit the complete sequence but elsewhere, including

this country, the sequence is incomplete as in Cheshire, Worcestershire, Middlesbrough and Carrickfergus.

Rock salt is obtained by mining or by brine-pumping, that is by the controlled circulation of water through boreholes. Gypsum is won by mining. It is interesting to recall that one of the first uses of coal in the North of England and in Scotland was for the production of common salt from seawater. Local reaction and replacement phenomena are best illustrated by the ironstones already described.

Detrital or "Placer" Deposits

The discovery of many parent ore bodies has been the result of working back to the source along detrital or "placer" deposits. Metals, particularly when native, are both heavy and resistant to weathering and are found as residual or surviving deposits near the outcrop (shoad deposits) or in streams or river flats through natural sorting because of high specific gravity. Gold, tin and platinum have been won by exploiting these placer deposits, the methods used being the direction of streams of water at high pressure by special jets or monitors and the collection of the heavy metal by cross-riffles in a series of troughs or launders, or solution in mercury in the bottoms of the launders in the case of gold. They may also be exploited by dredging from shallow streams or by bucket elevators on the banks of rivers and streams. Two-thirds of the world output of tin, in the form of cassiterite (tin oxide), is won by these methods which have been carried on by the "streamers" of Cornwall from the beginning of the Bronze Age.

Gem stones have also been recovered by these methods down the ages including diamonds in Brazil and South Africa, rubies and sapphires in Ceylon and topaz and tourmaline in Brazil and the Urals. Amongst the residual deposits bauxite, the most acceptable ore of aluminium, the importance to commerce of which in the light alloys bids fair to increase in the future, occurs in a restricted range of climatic conditions in which bacterial action removed quartz and silicates and left the alumina in a condition free from silica. The metal is then reduced in electric furnaces often supplied from an adjacent hydro-electrical station.

MASSES

Masses is a term used as an omnibus one to denote deposits which are neither beds nor veins. It includes a heterogeneous assembly of deposits such as bosses of granites, the blue ground or Kimberlite diamond-bearing volcanic necks and replacement ores like the haematites of Cumberland. The extent of masses can generally be

determined only by systematic diamond boring. The "stockworks," those networks of small veins interpenetrating rocks to such an extent that the whole must be excavated to extract the profitable ore (Fig. 109), are also sometimes included in this category.

Troy Weight

The concentration of valuable mineral in a vein, determined by some method of sampling of which the "spot" and the "groove" methods are most commonly employed, is necessary to determine whether the extraction will be economically worthwhile, and these concentrations, particularly in gold mining, are expressed in ounces per ton of material which is won from the vein which, to a large extent, consists of worthless veinstuff or gangue. The Troy system of weights in which 24 grains = 1 pennyweight (dwt), 20 dwt = 1 ounce (oz) and 12 oz = 1 pound (lb), which is the same as the pound Avoirdupois, is generally adopted.

APPENDIX

COAL WROUGHT AND COAL RESERVES IN GREAT BRITAIN

Since the dawn of coal mining in this country it may be estimated that nearly 20,000 million tons of saleable coal have been mined, the great majority since 1850. The estimated tonnages are—

Previous to 1800	850 millions
1800–1850	2,000 millions
1851–1956	17,319 millions

The total saleable output in 1955 was 221.6 million tons made up of a deep-mined output of 210.2 and an opencast output of 11.4 million tons and in 1956 the total saleable output was 222.1 millions of which 12.1 million tons was opencast coal.

The Coal Reserves remaining have been estimated by Royal Commissions on Coal Supplies on a number of occasions.

The 1871 Commission estimated the reserves in the British Isles to a depth of 4,000 ft as 90,207,000,000 tons in the proved and 56,273,000,000 tons in the concealed coalfields with reserves below 4,000 ft, at 7,321,000,000 tons, total 153,801 million tons.

The 1905 Commission estimated the reserves to 4,000 ft in the United Kingdom at 149,636 million tons with reserves below 4,000 ft in the proved coalfields of 5,239 million tons, total 154,975 million tons.

Estimates of reserves were also made by Strahan in 1913 of 179,000 million tons and in 1915 by Jevons of 197,000 million tons.

From the coal reserves put forward for valuation purposes under the Coal Act, 1938, by which the coal royalties were nationalized the Fuel Research Board with the aid of H.M. Geological Survey has carried out a "Rapid" or preliminary

survey (H.M. Stationery Office, 1946, price 9d) of coal reserves, and concluded that the "developed reserves" are 20,500 million tons available for extraction during the next 100 years and that ample reserves of all classes of coal required exist for considerably longer than this period, indicating that doubts concerning reserves are not justified for at least this period.

During 1945 and 1946 Regional Survey Committees were set up in each coalfield or group of adjacent coalfields to inquire *inter alia* into the present position and future prospects of the individual fields. The reserves remaining in each field were estimated as closely as the available evidence permitted but many of the Committees emphasized the need for extensive boring programmes to determine with any degree of accuracy reserves in the concealed fields.

The results summarized are as follows—

Coalfield	Reserves (Million tons)	Remarks
Kent	2,201	
Bristol and Somerset	198	In existing takes, boring required to estimate total
Forest of Dean	60	
South Wales	8,200	Excluding seams 12 to 24 in.
Leicester and South Derbyshire	783	Over 24 in. thick only
Warwickshire	878	To 4,000 ft only
South Staffs. and Cannock Chase	1,233	To 4,000 ft only
Shropshire (Forest of Wyre, Coalbrookdale and Shrewsbury)	126	To 4,000 ft only
North Staffordshire	1,686	To 4,000 ft only
Nottinghamshire	4,618	Proved 3,662, unproved 956, over 24 in. thick
North Derbyshire	1,957	Proved 1,891, unproved 66, over 24 in. thick
South Yorkshire	4,809	Proved 4,020, possible additional 789
West Yorkshire	2,007	Proved 1,677, possible additional 330
Lancashire and Cheshire	2,088	To 3,600 ft
North Wales	815	To 3,600 ft
Durham	3,000	Seams over 18 in. thick
Northumberland	2,102	Seams over 18 in. thick, proved 1,762, probable 340
Cumberland	583	Proved 312, unproved and probable 272 mostly undersea, over 18 in. thick
Scotland		
Lothians	1,230	
Central	901	
Fife and Clackmannan	4,135	
Ayrshire	1,146	
TOTAL UNITED KINGDOM	44,756	

The United Nations' Scientific Conference on the Conservation and Utilization of Resources, held at Lake Success, New York in 1949, in the Mineral Resources

section pointed out that those minerals in which world resources were low, without allowing for salvage, were chromite, copper, lead, zinc and tin. Coal, on the other hand, is relatively plentiful since with a world output of 1,510 million metric tons in 1948, reserves of 5,165,000 million metric tons gives a supply for 2,200 years, allowing for 35 per cent loss in mining. Attention was directed to the geographical factors of accessibility, climate, water and power supply, labour and food supply and the juxtaposition of resources, in the utilization of potential reserves where final cost to the consumer is the ultimate criterion. The trend of modern methods of discovery emphasizes the importance of geophysical methods of prospecting as a prelude to systematic boring programmes and attention is drawn to the saving in time and money by the use of aerial methods of magnetometer and gravimeter surveying where applicable and particularly in inaccessible terrain.

Mechanization to an increasing degree is visualized as the solution to rising costs of production.

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QUESTIONS

1. Give an account of minerals of economic importance, other than coal seams, associated with the Carboniferous System of this country.

2. Give an account of the different types of Ore deposits and explain their mode of formation.

3. What do you understand by (*a*) Primary Ore deposits, (*b*) Secondary deposits?

4. What do you understand by the following—(*a*) Secondary enrichment, (*b*) Masses, (*c*) "Placer" deposits?

CHAPTER XI

PROSPECTING

In the British Isles the exposed coal-bearing formations are well known particularly through the work of the Geological Survey. In the concealed fields, however, this is not the case, and as has been already mentioned, expensive boring programmes or other means will be required to determine the limits of these fields. Much useful information has already been garnered as a by-product of the recent borings for oil in this country, particularly in Lincolnshire and Derbyshire in the Eakering district. In less well geologically-serviced countries, however, and in the elucidation of minor problems such as the recovery of seams displaced by faulting and the search for coal accessible by open-cast methods in this country prospecting is required. Coal weathers quickly when exposed on the surface so that, except where exposed by deep valleys or in cliff faces, outcrops of seams are difficult to find.

The seams and associated shales and fire-clays generally contain pyrites and "ochrey" streams coloured by iron oxides produced by the oxidation of pyrites may, if followed, lead back to the coal outcrop. Ice-carried fragments of Coal Measure rocks are of small utility as they may be found many miles from the parent mass. Fossils give reliable evidence but considerable numbers are requisite, particularly fresh-water fossils, as there was considerable "spread" of fossils and they are of no great help in the search for a particular seam. On the other hand if all the fossil evidence is marine then the presence of Coal Measure strata at surface cannot be expected. It should not be forgotten however that marine bands, of which the Mansfield already referred to is one of the best known, are of the greatest possible use in fixing the horizon in the Coal Measure succession.

As much of the solid geology of the district under exploration will be covered by rain-wash, vegetation and alluvium, the best possible use must be made of such exposures that do exist in order to construct a geological map and sections of the region. These will include crags and bare rocks on hills or exposed by streams, colour of the soil, soil thrown out by burrowing animals and cuttings for railways, roads, well sinkings, drainage or other works. Vegetation, particularly trees, often exhibit a preference for certain formations and large

scale geological reconnaissance by aeroplane has made use of this selection of certain strata by distinctive plants or trees, while the difference in the depth of colour of grasses, etc., on different rocks has been found useful in tracing the junction between dissimilar beds. In metal mining the mineral sort is generally more resistant to weathering and throughout the ages prospecting for minerals has employed the method of tracing "float"—pieces of the mineral sought broken off the parent mass by agents of denudation—back to its source. A further development of this is "panning," the examination of river silt for native metals or heavy sulphides which are separated out by water-washing in a pan 4 to 6 in. diam or in a frying pan.

Trenching may have to be resorted to, from 1 to 7 ft in depth, to (*a*) obtain "float" under a cover of vegetation or silt (*b*) uncover the bed rock or a particular horizon or junction of beds. Trenches in mineral prospecting are run at definite intervals of 50 to 500 ft at right angles to the assumed line of strike of the ore body or the strike of an inclined coal seam.

Probing by pointed steel rods may be used to find harder or softer minerals in a country rock of opposite hardness or to determine the depth of silt or other soft strata to bedrock. Pipes one or two inches in diameter with a cutting edge and a cap to preserve the threaded top may be used to take samples of the soil every foot of depth. Further pipes may be screwed on until hard strata which cannot be penetrated is reached. Alternatively a hand-operated drill may be used to penetrate to a depth of about ten feet. Where the alluvium is too thick for trenching, test-pits may be dug and may attain a depth of 100 ft. The material excavated is removed by a bucket wound out by a hand windlass and hemp or $\frac{1}{2}$ in. diam wire rope. The pits are of small diameter, 2 ft 6 in. to 3 ft, and a short-handled pick and shovel are used.

Boring is the main tool of both surface and underground exploration but drilling is so costly that it is only employed when prospecting has already revealed the probability of the coal or mineral field looked for. Although fields of great richness, from which among others gold, diamonds and copper of great value have been won, have been discovered by a happy chance or by prospectors of great experience and toughness but with the most primitive equipment, these more or less easy plums can in the future be expected to be few and far between. More and more discoveries of new fields are the result of carefully planned prospects employing intricate and expensive scientific equipment and highly trained specialists. This is particularly the case where the mineral is covered by a great thickness of

overburden which may give no indication at surface of the type of geological structure at depth with which the occurrence of the mineral is generally associated. This is the case in oil exploration and in searching for metalliferous minerals but these are not without interest in coal mining, as faulting and folding in the concealed fields under considerable unconformable cover of newer rocks may, perhaps with difficulty, be revealed by the same means and assist in the planning of future workings with greater certainty than hitherto.

GEOPHYSICAL PROSPECTING

These scientific methods of prospecting are known as geophysical systems and are used in conjunction with geological co-operation which indicates the limited areas in which the type of formation required is likely to be found. This may in turn suggest the method of geophysical prospecting most likely to be successful, although a combination of two methods, confirming or supplementing each other, is often used. This restriction of effort is necessary as geophysical surveying is expensive in cost of instruments, and running expenses including in remote places the costly special accessories of camp life, though use of aeroplanes and helicopters can reduce the cost very substantially.

The basis of geophysical methods is the differentiation, usually abrupt, of some physical property as between rocks. These local variations or "anomalies" naturally produced or artificially stimulated are generally small and require delicate measuring instruments whose results need skilled interpretation.

The four main methods employed are—(*a*) gravitational, (*b*) magnetic, (*c*) seismic and (*d*) electrical, depending respectively upon differences in rocks below the surface of (i) density, (ii) magnetic susceptibility, (iii) velocity of elastic wave propagation and (iv) electrical conductivity or electrical self-potential.

Gravitational Methods

In this method minute changes in the force of gravity are used to interpret strata distribution underground, such as those produced by the denser rocks of the core of an anticline compared with the rocks on the flanks, low density salt domes, rock faults, haematite and brown coal deposits. The instruments which may be used are—(*a*) Pendulums and crystal clocks for absolute measurement of gravity at stations, (*b*) Gravimeters which measure the change in gravity by means of the extention produced in a spring and (*c*) torsion balances which were first used by Baron Roland Von Eötvos in 1915. The basis of this instrument is a torsion wire suspending two weights on a

light beam, one weight above and the other below the point of suspension (Fig. 111). Both weights are attracted by the strata beneath, the lower weight m_1 being nearer is subject to stronger attraction than the upper, m_2, both attractions being in accordance with the inverse square law. The suspended system will turn until the torsion in the wire T balances the differences in the couples due to the two weights. The instrument must be orientated in several

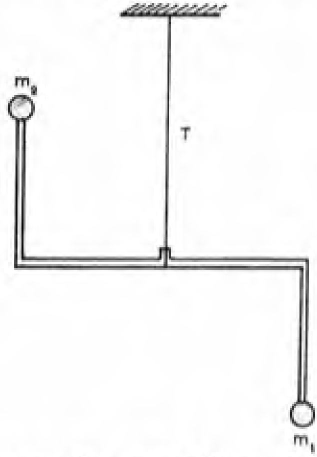


FIG. 111. ESSENTIAL ELEMENTS OF EÖTVOS TORSION BALANCE

directions to determine the direction and magnitude of the force to be calculated. The changes in gravity measured are very minute amounting to one thousandth of a gal (Galileo), the gal being the strength of field acting on a mass of 1 gram with a force of 1 dyne, thus one gal = 1 cm/s^2 so that the Earth's field is 981 gal and a milligal approximately 1 millionth of the Earth's field. To interpret results they are compared with computed anomalies for different geological structures until a match is obtained.

Magnetic Methods

This is the oldest method of geophysical prospecting, being used in the seventeenth century by De Castro, and is the simplest and least costly in practice. It consists of measuring with portable magnetometers or variometers local variations of the vertical and horizontal components of the Earth's magnetic field, i.e. changes in the magnetic inclination and declination respectively. The basis of the method is, therefore, the differentiation of the magnetic susceptibilities of different rocks. The distortion of the Earth's field or the anomaly will

only be measurable if the rock structure responsible has a large susceptibility, such as a ferruginous mass (Fig. 112), or dyke of basic igneous rock, such as basalt, containing a considerable quantity of iron.

In recent years, however, the sensitivity of variometers has been increased to 5 gamma (100 thousand gamma = 1 oërstead or c.g.s. unit). The chief corrections to be applied, which are particularly

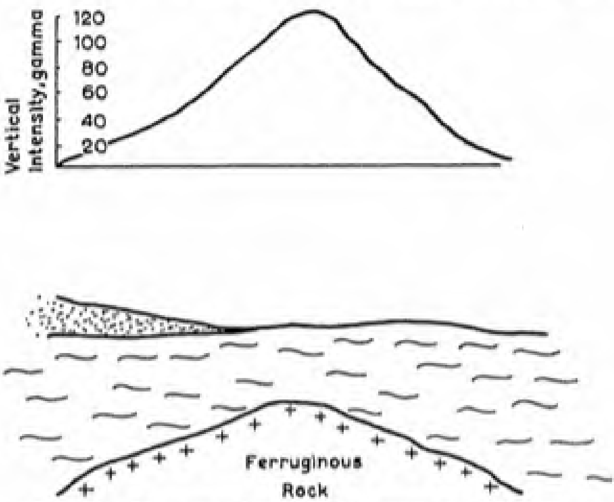


FIG. 112. MAGNETIC ANOMALY MEASURED BY A VERTICAL FIELD MAGNETOMETER

necessary when employing the method to rocks of relatively low susceptibility where the readings are near the limit of the instrument, are those for diurnal variation of the Earth's field and for temperature changes.

Two systems of magnetic surveying may be employed—(*a*) with the swing of the needle in the direction of the Earth's magnetic field when the susceptible structure is at one side of the magnetic profile, (*b*) with the needle swinging at right angles to the Earth's field so that only the vertical component of this field is effective. The maximum deflection then occurs directly over the susceptible structure.

Modern instruments are generally of the magnetic balance type (Fig. 113). The initial deflection of the instrument due to the Earth's field is counterbalanced either magnetically or by means of a weight. A magnet is supported so that its axis lies in a horizontal plane and perpendicular to the magnetic meridan, thus eliminating the effect of the Earth's field horizontal component so that only the vertical

component tends to tilt it. This tendency is neutralized by a small counterbalance weight, the position of which gives the reading taken by means of an optical system. The swing of the needle is damped by means of pure copper dampers.

Seismic Methods

These methods are applications of the same principles used in permanent apparatus at seismological stations for recording earthquake shocks to portable apparatus, which picks up and records

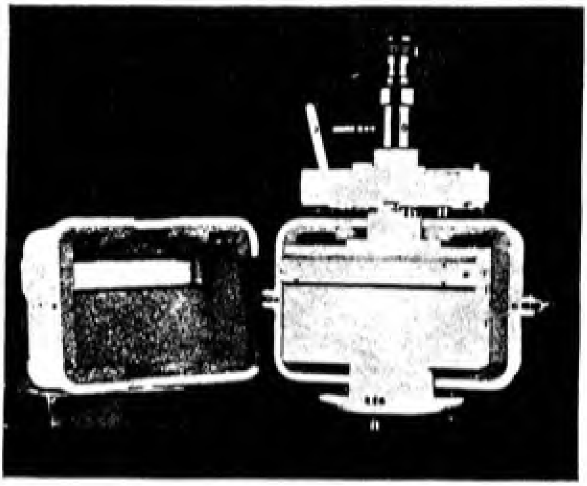


FIG. 113. HILGER AND WATTS' VERTICAL FORCE VARIOMETER
Note cork-lined case for heat insulation.

small earthquake shocks, artificially generated by firing charges of explosive in the area to be investigated. The observations obtained enable time-distance graphs to be plotted of the paths of the compression waves which have been reflected and refracted at surfaces of discontinuity between rocks before arriving at the recorders.

These waves travel at different speeds in different formations and successful application of the method to the elucidation of the dip and folding of strata and the depth below surface of one or more particular beds requires a large velocity-ratio between the rocks under the area. The method has been useful in prospecting for oil by the location of salt domes under alluvium, of anticlines in limestones and deep granite basements. The presence of the mineral sought is, of course, not directly indicated but geological structures are revealed in which the probability of its occurrence is to be inferred.

FIG. 114. PORTABLE SEISMIC GEOPHYSICAL PROSPECTING EQUIPMENT (CRAELIUS)

The method was first used by Mintrope in 1919. For relatively shallow work, for example the determination of the depth of the rock-head below alluvium and drift for foundations of heavy surface structures or salt domes in oil prospecting, the refraction method is used. To elucidate deep-seated structures down to depths as great

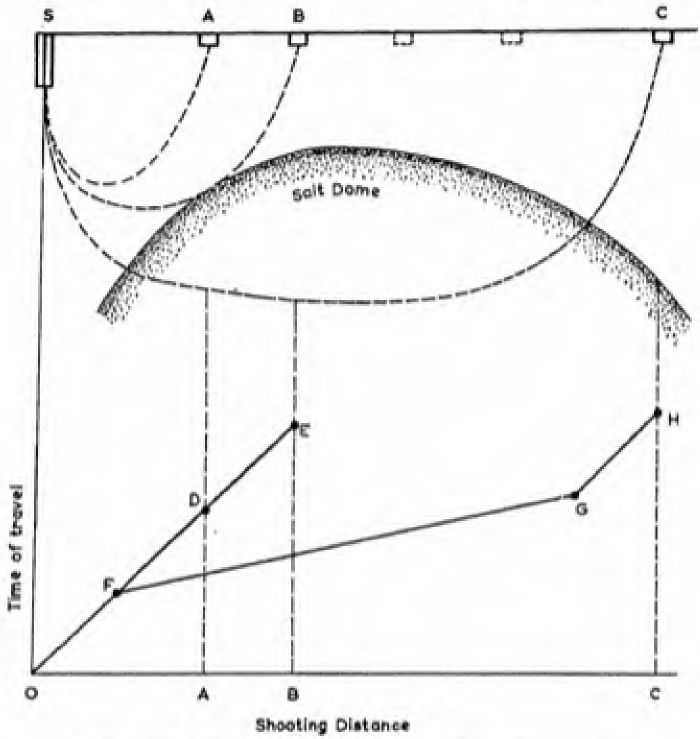


FIG. 115. REFRACTION WAVES IN SALT DOME STRUCTURE

as 20,000 ft the reflection method is adopted which is closely akin to echo-sounding to determine the depths of the oceans.

The apparatus and mode of procedure is similar whether the refraction or the reflection method is used (Fig. 114). Explosive is fired in a borehole from ten to some hundreds of feet deep in order to penetrate the zone of weathered strata in which the compression waves would travel at low speed. The recorders which pick up the refracted or reflected waves are also generally buried to shield them from wind and other sources of interference.

The mechanical movement imparted by the waves to the recording

seismographs is converted to an electric impulse which is amplified, particularly the weak wave from deep-seated structures where the reflection method is used. An oscillograph is fitted and records the instant of firing the explosive charge which breaks a wire wound round the charge. The electrical impulses from the amplifier cause deflection of the light beam of the oscillograph which then passes through a condensing lens and is photographed on a moving roll of sensitized film. At the same time light from a second beam is deflected by a metronome and records time intervals simultaneously on the film.

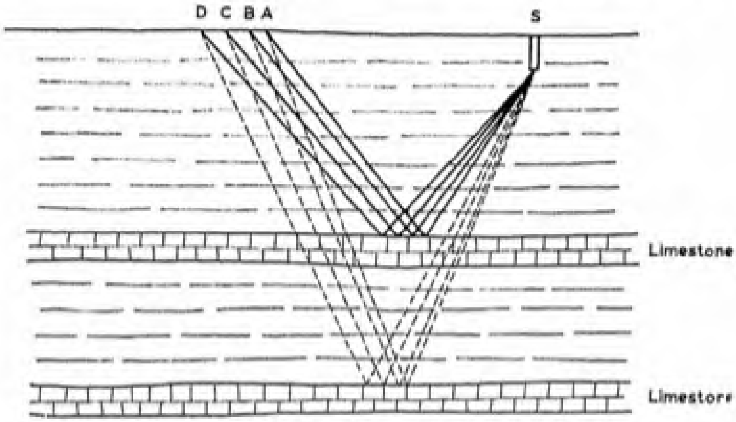


FIG. 116. REFLECTION METHOD FOR DEEP-SEATED FORMATIONS

Groups of such recorders are distributed over the area under investigation. Fig. 115 shows the principle of the refraction method applied to the search for salt dome structures.

From the shothole *S* waves *SA* and *SB* pass to the recorders at *A* and *B* without penetrating the salt dome. Assuming normal strata the velocity of the waves would be of the order of 6 thousand ft/s and the velocity/time curve would be the line *OFD* and *OFE* respectively. The wave *SC* penetrates the upper strata, is refracted and passes through the salt dome in which its velocity will be about 16 thousand ft/s and then again passes through the normal strata to the recorder at *C*. The velocity/time curve for this wave is *OFGH*. The portion *FG* in the salt dome is less steep than in normal strata by reason of the much higher velocity.

The application of the reflection method is shown in Fig. 116. Two limestone bands give indications on four recorders *A*, *B*, *C* and *D* of the echoes produced by a charge fired at *S*, the echoes arriving in two separate groups, that from the upper band first.

Electrical Methods

These methods fall into four groups—(*a*) Self-potential system, (*b*) Surface potential methods, (*c*) Ground resistivity methods, (*d*) Inductive methods.

In the self-potential system the electric field is due to the oxidation of sulphide ores which may give potential differences of 20 millivolts in 100 ft. The area to be investigated is traversed by parallel

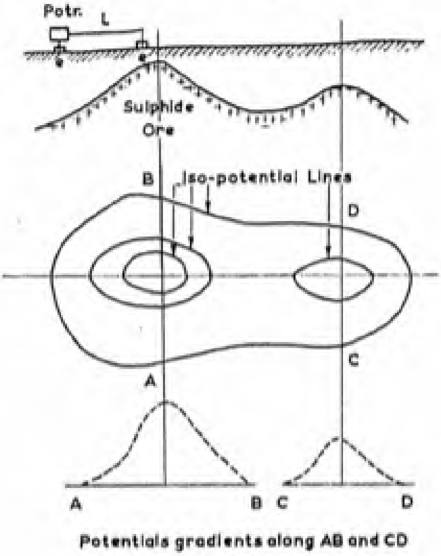


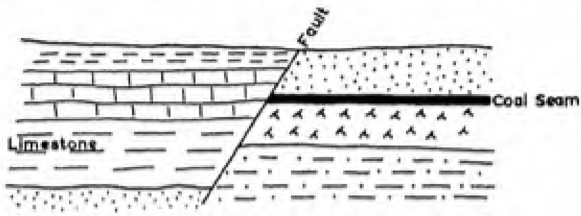
FIG. 117. SELF-POTENTIAL SYSTEM

lines of stations and then points of equal potential are joined, giving isopotential contours.

The apparatus used consists of two porous pot non-polarizing electrodes *e e* (Fig. 117), connected by insulated leads to a sensitive potentiometer reading to 1 millivolt. Two methods of surveying may be adopted, the traversing method in which the electrodes are a short distance apart *L* (Fig. 117), and the traverse proceeds in one direction, the rear electrode occupying the position previously taken by the leading electrode in the previous reading. The second method is known as the fixed electrode method in which one electrode remains stationary while the other is grounded at progressively greater distances from it. The method, shown in Fig. 117, indicates the mineral sought directly beneath the greatest anomaly and has been extensively and successfully used to prospect both mineral ores,

such as pyrite, chalcolpyrite and galena, and insulating materials like cinnabar and stibnite.

In the surface potential method earthed electrodes are connected



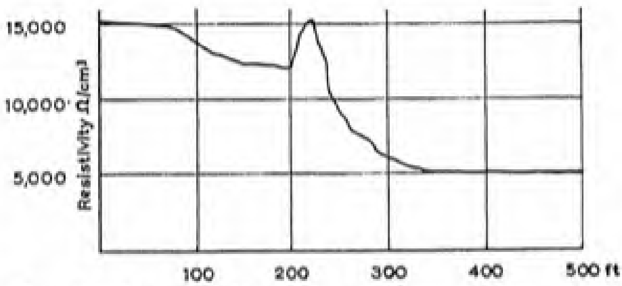


FIG. 118. RESISTIVITY VARIATION IN DIFFERENT STRATA ADJACENT THROUGH FAULTING

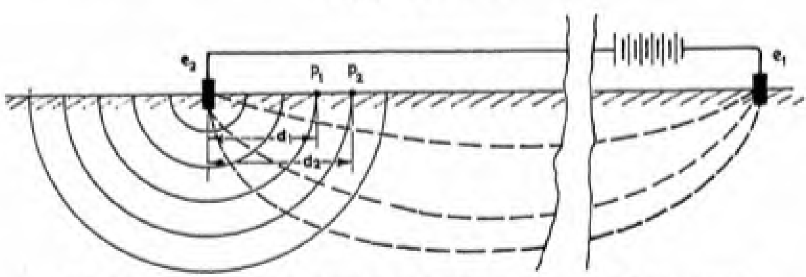


FIG. 119. SCHLUMBERGER METHOD OF GROUND RESISTIVITY PROSPECTING

to a source of electricity and the current distribution on the surface is mapped by means of equipotential lines.

The ground resistivity method, of which there are a number of different systems, determines the apparent resistance in ohms/cm³ to the passage of current through rocks (Fig. 118). In the Schlumberger system (Fig. 119), the electrodes e_2 and e_1, through which the current

from an accumulator of some 220 V passes, are placed far apart and the potential drop measured by means of two non-polarizing electrodes p_1 p_2 near one electrode e_2. As p_1 and p_2, which are kept a

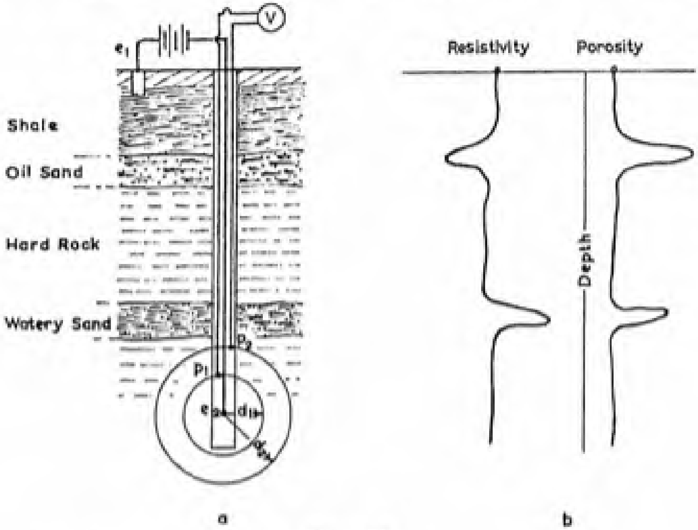


FIG. 120

(a) Schlumberger Method of Resistivity and Porosity Borehole Surveying.
(b) Schlumberger Resistivity and Porosity Logs.

constant distance apart, recede from e_2, the resistance of deeper rocks is measured.

If d_1 and d_2 are the distances in cm of p_1 and p_2 from e_2, then the resistivity is given by the expression—

$$\text{Resistivity in ohms/cm}^3 = \frac{2\Pi d_1 d_2 \mathrm{V}}{(d_2 - d_1)\mathrm{I}} = \frac{2\Pi d_1 d_2 \mathrm{R}}{(d_2 - d_1)}$$

the voltage being measured with a potentiometer and the current by a milliammeter, or the resistance by means of a modification of the megger testing set.

This system is also used in boreholes to measure the resistivities and porosities of the formations penetrated by the drill. One current electrode e_2 (Fig. 120), is lowered into the hole above which are two potential electrodes p_1 and p_2 at distances d_1 d_2 above it, the battery and the second current electrode, e_1, being at surface. The current I from the battery is maintained at a constant value and the potential V is measured by a recording potentiometer automatically on a chart

in relation to depth. The resistivity of the strata between d_1 and d_2 is given by the expression

$$\frac{4\Pi\ V d_1 d_2}{I(d_2 - d_1)}$$

For the determination of the porosity of the beds, important in prospecting for oil-bearing sands, a potentiometer is connected between the electrode at the bottom and the second electrode at the surface. High potentials indicate penetration of drilling mud into porous beds. High resistivity indicates hard formations or oil-

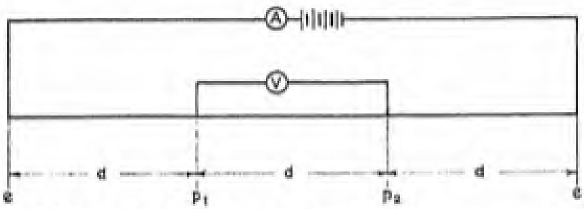


FIG. 121. WENNER ARRANGEMENT OF CURRENT AND POTENTIAL ELECTRODES

FIG. 122. SUCCESSIVE POSITIONS OF ELECTRODES IN TRAVERSING SYSTEM

bearing sands but the former have low and the latter high porosity. Sands with saline water show low resistivity but high porosity. By surveying adjacent wells, faults and the folding of the strata between are indicated.

In the Wenner system and later modifications the distances apart of the current and potential electrodes are equal as shown at d in Fig. 121. Deeper penetration is obtained by increasing the distance apart of the current electrodes e and e_1. In the traversing method used to determine lateral changes of strata the current and potential electrodes are moved progressively along a line, as shown in Fig. 122. In order to eliminate self-potentials, reversing switches are provided on both current and potential circuits.

In modifications of the Wenner method, particularly the Gish-Rooney, low frequency alternating currents are used in place of direct current by means of the use of a hand-operated commutator system in order to eliminate self-potential. In the Inductive Methods alternating current with a uniform frequency, generally about 500 c/s,

is used and two current electrodes are grounded as in the Wenner and kindred systems. The primary current induces secondary currents in the strata through which the primary current passes and the resulting magnetic field at the surface is distorted in phase and direction by the presence of anomalies.

Two main systems are employed. The first employs a coil related in diameter to the depth to be penetrated, and the magnetic field induced is measured by a single- or two-coil system. In the second, the current electrodes are connected by a long insulated cable laid on the ground to be investigated, and short traverses at right angles to its course are made with a pair of coils a fixed distance of about 60 ft apart, to measure changes in phase and amplitude between the induced voltages in each coil. In this, Turam, method phase differences are contoured by iso-phase-difference lines and when these approach each other, indicating a steep gradient in the rate of phase-difference change, minerals may be expected.

Other physical properties which are made use of in certain projected methods of prospecting yet in the experimental or speculative stage are temperature surveys for the discovery of formations with high thermal conductivity, measurement of the radio-active content of soils and, in particular, of the radium content and micro-gas analyses of soils as an indicator of oil deposits. In addition to the recovery of cores from boreholes and, in some cases as a substitute for core-boring, geophysical and other methods are used to provide supplementary information from boreholes.

The rate of penetration of the various rocks may be continuously recorded and since every type of rock, if the pressure on the bit and the rate of rotation are constant, gives a distinct rate of penetration so that junctions between different beds are indicated. In addition, as coal is more easily penetrated than other Carboniferous strata, the position and thickness of a seam is recorded and checked against the core samples.

The porosity of the beds, both on a normal and on a micro-scale, is measured by the electrical resistivity method; the radio-activity and the self-potential, produced by interaction between the water in the drilling mud and that in the strata, are all measured and recorded continuously and are known collectively as the Schlumberger logs (Fig. 123).

The Micro-log is a refinement of the electric resistivity log. Its

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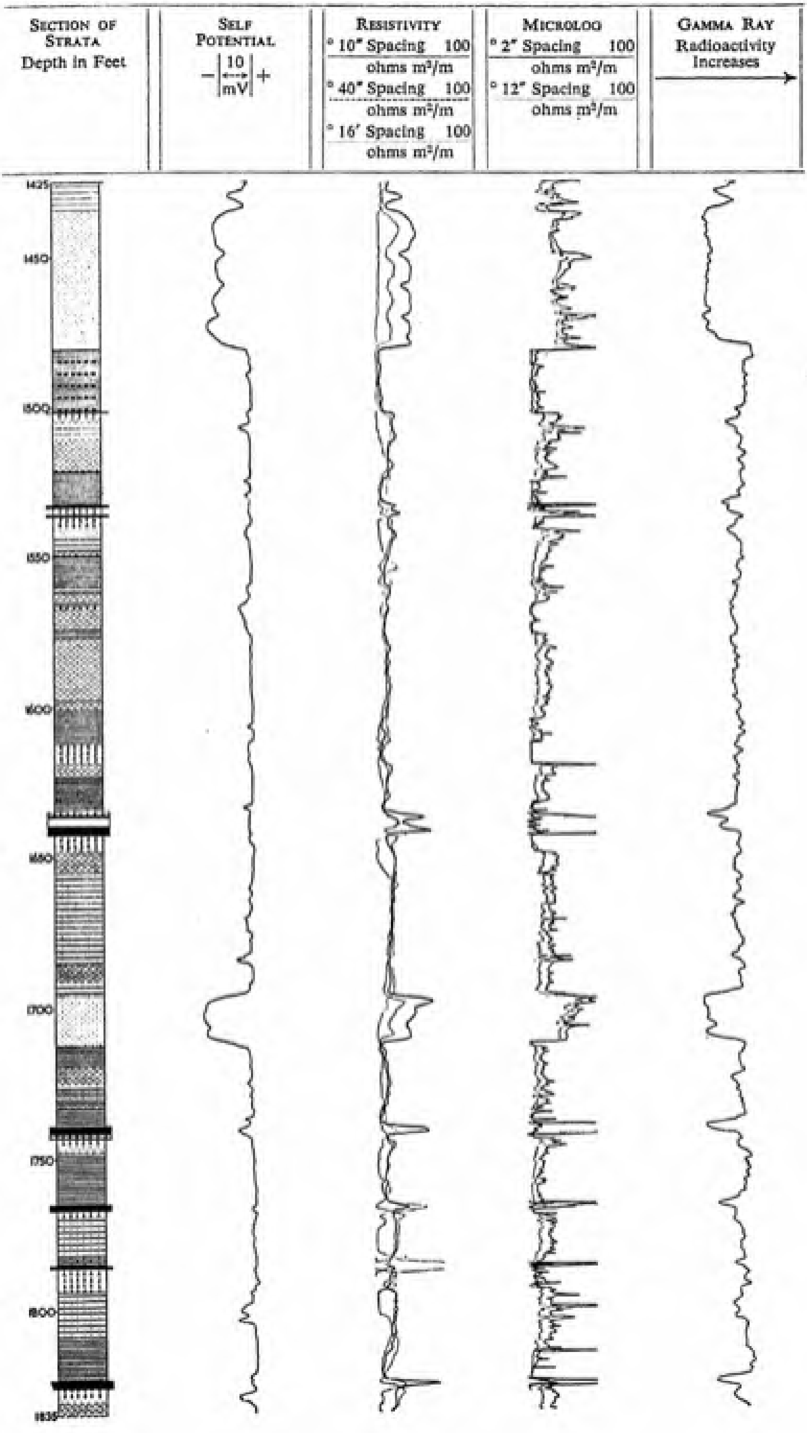
FIG. 123. SCHLUMBERGER LOGS COMPARED WITH GEOLOGICAL SECTION

(Reduced approximately three times.)
N.C.B. BULLETIN]



SECTION OF STRATA
Depth in Feet
SELF POTENTIAL
− 10 mV +
RESISTIVITY
10" Spacing 100 ohms m²/m
40" Spacing 100 ohms m²/m
16' Spacing 100 ohms m²/m
MICROLOG
2" Spacing 100 ohms m²/m
12" Spacing 100 ohms m²/m
GAMMA RAY
Radioactivity Increases
1425
1450
1500
1550
1600
1650
1700
1750
1800
1835

close spaced electrodes are pressed against the wall of a boring while in taking the resistivity log the electrodes are widely spaced and hang free in the mud-filled hole.

Some radio-active material is present in most rocks. The gamma ray log is utilized to indicate the relative concentration and, since this is related to some extent to lithology, it provides a clue to the stratigraphical succession. The so-called neutron log measures the kinds of fluids in the interspaces of a rock. Unlike the electrical logs the radio-active log may be taken in a cased hole.

These records reduce the number of cored holes required to interpret the geological structure of an area and the correlation of the coal seams in it. The Schlumberger logs require a period of 8 hours for a 3,000 ft deep hole, but in friable strata which must be cased, they are taken at more frequent intervals, about 800 ft, before the casing is inserted.

Trials are being conducted with the Tectonometer consisting of a radio transmitter and receiver with a directional aerial. The strength of the signal received is measured and this is affected particularly by fractures in the strata. The method has been used to determine the fault pattern in an area but "ghost" lines also are produced which are not due to faulting.

QUESTIONS

1. Describe how a district may be prospected for coal deposits and indicate how the nature of outcrops found has a bearing on initial development of the deposits.

2. Give a brief account of prospecting for minerals by means of either magnetic methods or electrical methods.

3. Write an account of the geophysical methods used for determining the tectonic structures of an area.

4. Give an account of (*a*) Gravitational methods, (*b*) Seismic methods of geophysical prospecting.

5. What do you understand by the Schlumberger Logs? Indicate the type of information these supply and how this information may be used.

6. How may the principles of geophysics be applied in prospecting for minerals? Indicate the application of the chief methods used.

CHAPTER XII

BORING

In a previous chapter the necessity for boring and its importance has been indicated. It is a very old technique and the older hand methods have been used for centuries.

The main problems to which boring may give the key vary in magnitude from the discovery of a mineral vein, oil sand or coal seam at a depth from a few feet to 15,000 ft below the surface, to the obtaining of samples and a record of the thicknesses of such deposits so that their commercial value and possible economic extraction may be appreciated. When conducted from underground workings, boreholes may be used to recover coal seams and mineral veins displaced by faults and other geological accidents or to determine the size and economic limits of an ore-body. In addition they may be used to determine the position of and to tap volumes of water in disused workings which would otherwise menace later developments. In addition borings from the surface may be put down to determine the depth of bed-rock below drift or other loose strata upon which foundations for heavy structures may be constructed safely, for the supply of water, saline solutions or to conduct power cables or ventilation to underground workings.

So that in addition to its value in exploration, the exploitation of the mineral, such as oil, and soluble minerals like rock-salt, may be carried out directly through boreholes. In the main, however, in coal and metal mining the most important function of boring is exploration and as speed of boring and cost are closely interrelated, the purpose for which the hole is being put down should not be forgotten. It is essential that proper records and proper samples of the strata penetrated should be kept with the greatest possible accuracy and details with checks, wherever possible, from sludge returned from the hole with the water used to convey it from beneath the boring tool.

Boring methods may be subdivided into hand methods, generally percussive, power driven percussive methods including rope methods and rotary methods in many of which cores of the strata penetrated are recovered.

The speed of boring and the percentage recovery of ore have increased to a remarkable extent in the last few years.

HAND METHODS

The simplest method of boring and one limited to depths of 50 ft where two men are employed and to 80 ft where three or four men are used is the brace-head and rods percussive method shown in Fig. 124. The tools used consist of a chisel bit *A* or a cross bit *B* for harder rocks, generally 2 to 3 in. wide, screwed to a line of square shaped wrought iron rods about 1 in. square with round screwed and socketed ends *C*, the length of which are generally 6 ft with a few shorter lengths. The rods are raised and turned, so that the chisel bores a round hole and does not jam, by means of a single, *D*, or double brace-head, *E*. Water is fed into the hole and at intervals a sludger, *F*, on a thin wire rope or substituted for the chisel at the end of the rods is lowered into the hole and, by means of the ball or flap-valve at the base, the cuttings and sludge at the bottom of the hole are worked into the barrel of the sludger by reciprocating this in the hole. The sludger is then raised to the top of the hole and its contents examined, this being the only evidence obtained of the strata penetrated. The rods are unscrewed and prevented from falling back down the hole by means of the gripping and retaining keys, *G* and H, which grip the square rods above and below the joint being unscrewed. The rods are screwed together, when again lowered into the hole, in the same manner. This method is limited in scope and is used to determine the thickness of beds near the surface, or to recover seams cut off by faults. In the latter case, a stone drift is driven well clear of the fault fissure and then the hole is put down; if the seam is recovered, that is if the fault is a downthrow, the haulage road may be graded to recover the seam and facilitate future haulage operations.

If the boring takes place through clay, an auger, *I*, replaces the chisel. Such tools are also used to bore wells from 6 in. to 2 ft in diameter. In the Banka type of drill a steel platform screwed to lengths of casing tube supports four borers who operate a percussive system taking samples by bailer or by a core barrel through the casing tubes, the latter being turned as they descend by four men at the end of a long pole.

For deeper holes a derrick, *C* (Fig. 125), and either a pivoted beam, *A*, or a spring pole is used. If the former, the beam of fir, larch or ash, is used to raise the rods by lowering the beam, which raises the shorter end to which the rods are attached through the stirrup, *B*. This allows the rods to be turned by a master borer by means of the tiller, *E*. The derrick is generally of wood about 20 ft in height and is fitted with a windlass, *g*, with about 50 ft of rope which is attached

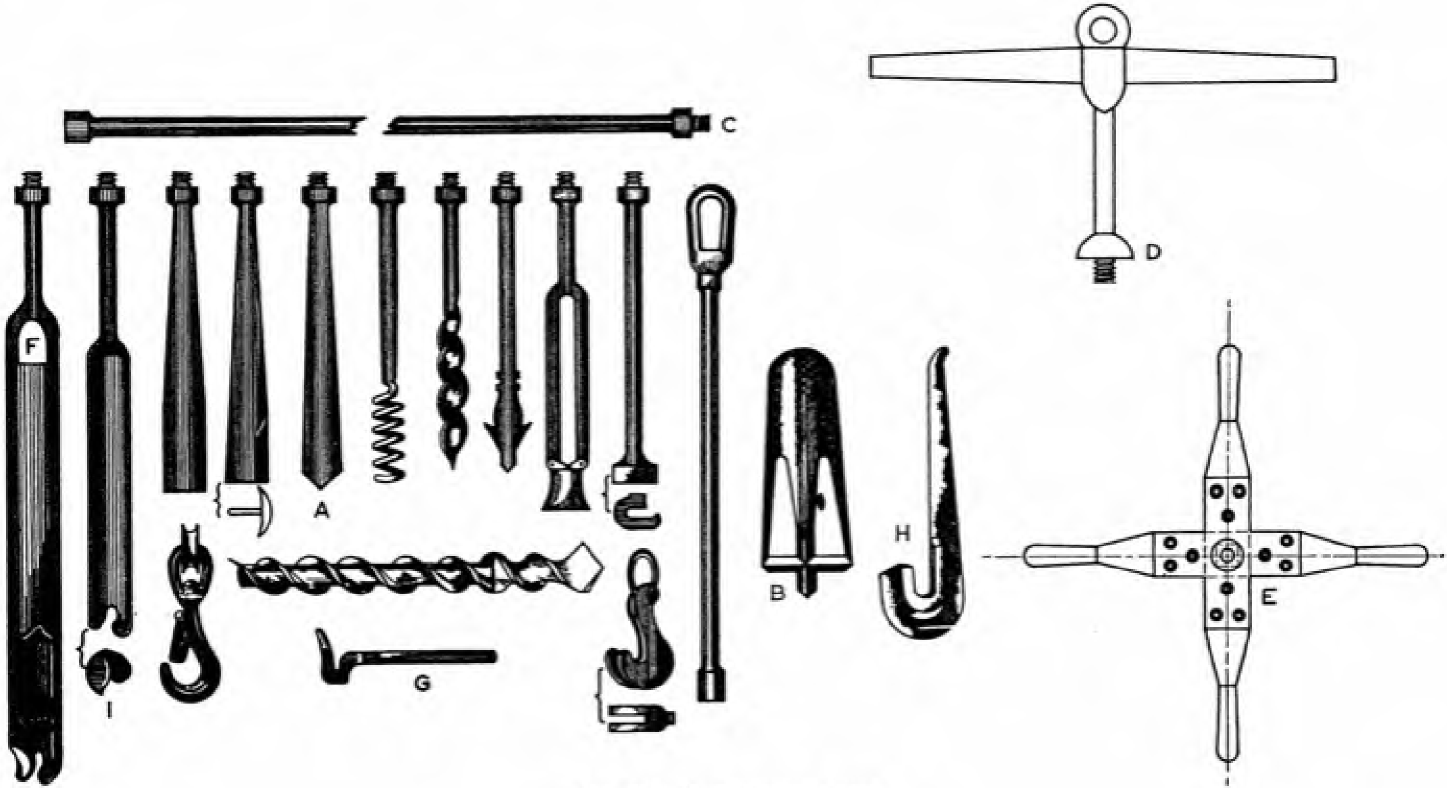


FIG. 124. HAND BORING TOOLS

to the rods through a swivel, allowing the rods to be turned. The windlass is used to raise the rods when it is necessary to lift and unscrew them to change the chisel or to clean out the hole by means of the sludger. Longer rods, from 10 to 15 ft in length can be used in conjunction with a taller derrick which reduces the labour of screwing and unscrewing rods. The beam gives a leverage of about 6 to 1.

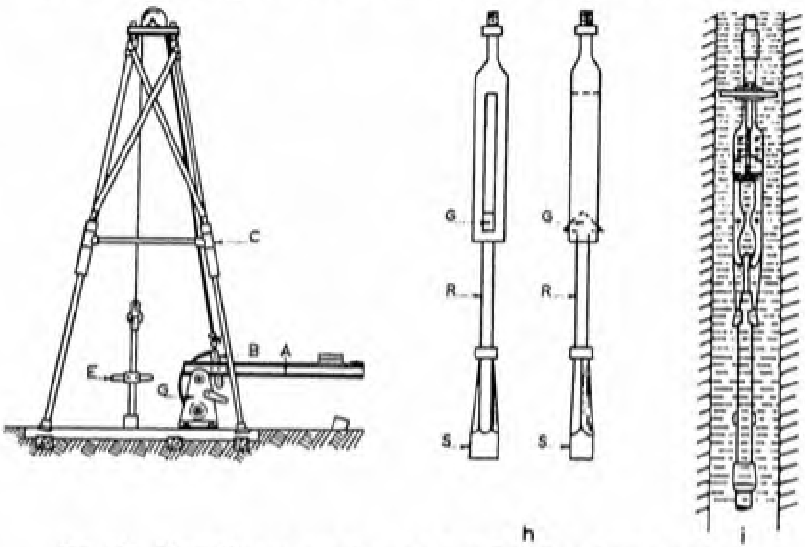


FIG. 125. HAND BORING WITH DERRICK AND FREE-FALL JOINTS, *h* AND *i*

As the hole gets deeper the weight of the rods descending may cause the breakage of the chisel or the lower rods and "jars" or "free fall" sliding joints *h*, and *i*, may be inserted. Thus in one of the earliest types, Oeynhausen's, shown at *h*, the slot in which the cross-head *G*, to which the lower rods, *R*, and the chisel, *S*, is attached, slides is greater in length than the stroke imparted by the beam to the upper rods and the lower rods and chisel fall independently.

In the type shown at *i*, known as Kind's, a pair of tongs are attached by their upper ends to a sliding block fitted with a disc of leather and iron rings somewhat less in diameter than the hole. The lower rods and chisel are attached to a sliding joint with a pear-shaped top which is gripped and lifted by the tongs when the upper ends are pushed apart by the resistance of the disc as the rods are lifted. When the rods descend, the resistance of the disc causes it to be lifted by the water in the hole relative to the rods and pulls towards each other the short ends of the tongs. This causes the lower ends to

separate and release the pear-shaped head and the lower rods and chisel. The "jars" also assist in dislodging the chisel on the up-stroke should it tend to stick.

When a spring pole is used it consists of a whippy pine about 6 in. diam at the hole end and about 10 in. at the anchored end. The fulcrum is nearer the anchored end giving a leverage of from 3 – 5 to 1. The swivel on the rods is attached to the spring pole by a short length of manila rope. These deeper holes are generally started through a vertical stand-pipe for direction and also to prevent caving of loose surface soil into the hole.

ROPE DRILLING

This method was developed in particular for rapid oil-well boring and is still used for nearly half of the footage bored for oil, particularly for the shallower holes less than 6,000 ft in depth. The arrangement of the plant (Fig. 126), has been standardized which facilitates erection and dismantling and limits the cost of spare parts. The rope used is either of untarred manila, hawser laid, about 6 in. in circumference or a six-strand 19-wire steel rope. The rope is coiled on a bull-wheel, *b*, and is led over the crown pulley, *A*, at the top of the derrick which is 72–84 ft in height, of wood or more generally steel sections or steel tubing with a base about 20 ft^2.

In order to transmit the necessary weight to the boring tool, a string of fittings is inserted between it and the rope socket so the derrick needs to have considerable height to enable the string to be swung clear of the hole for the clearing of cuttings. This is performed by the sand pump or bailer which is lowered and raised by means of a 6-strand wire rope which winds on the sand reel, *f*, driven by frictional contact with the main driving wheel, or band-wheel, *i*, contact being established by the lever system *g* connected to a handle on the derrick floor. The boring tool for this percussive system of boring consists of the straight or Mother Hubbard type of bit for hard rock, *a* (Fig. 127), or a cross-bit *b*, for hard fissured rocks, while the spudding bit, *c*, is used to penetrate the loose surface soil and gravel for the first 100–200 ft of the hole. This operation is known as "spudding" and the spudding bit is attached to an auger stem, *d*, from 16–48 ft in length. This in turn is screwed into a rope socket at the end of some 200 ft of rope which is led over the crown pulley to the bull-wheel. There are two methods of reciprocating the bit and auger stem up and down to bore through the relatively loose surface beds. In one method the rope is wound once or twice round the bull-wheel shaft which is driven by a crossed rope drive from the band-wheel. The latter is rotated by means of a belt from the

driving pulley of a 12 in. diam and 12 in. stroke to 14 in. by 14 in. steam engine of the single-cylinder type supplied by a 40 or 75 h.p. boiler with steam at a pressure of 100–150 lb/in.^{2}. Alternatively, a

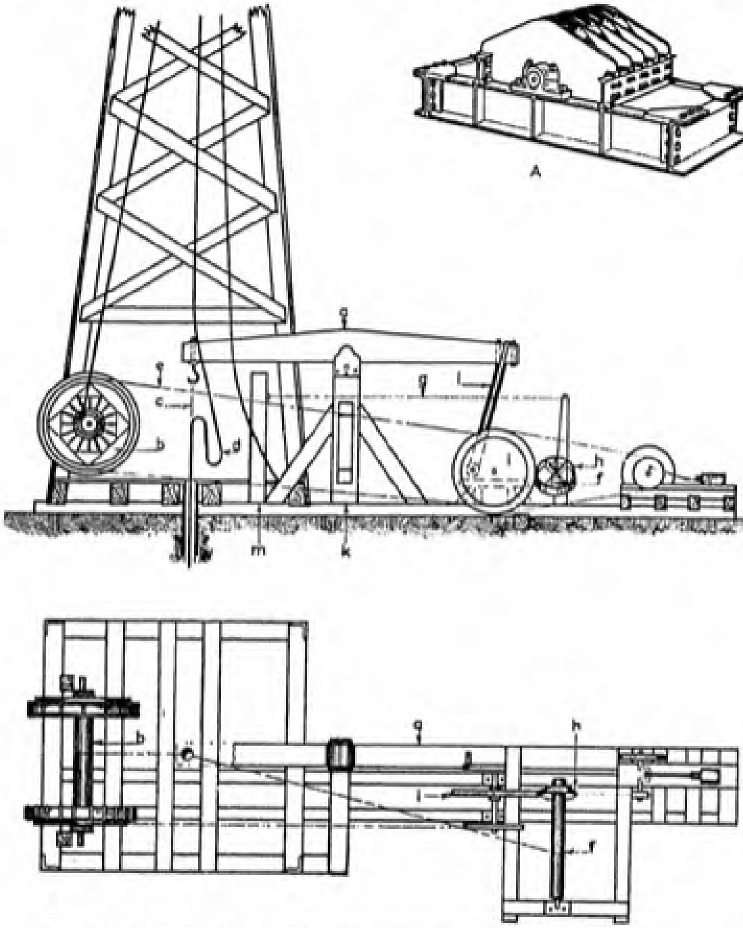


FIG. 126. DRIVING MECHANISM FOR AMERICAN ROPE DRILLING SYSTEM

A. 4-sheave crown block for 66,000 lb (Craelius).

diesel or petrol engine of 50–150 h.p., depending on the depth to be drilled, or a single or double electric motor drive of 25–130 aggregate h.p. may be used. The borer holds the loose end of the rope and by alternately tightening or slackening the rope on the revolving bull-wheel shaft the tools are raised and then dropped.

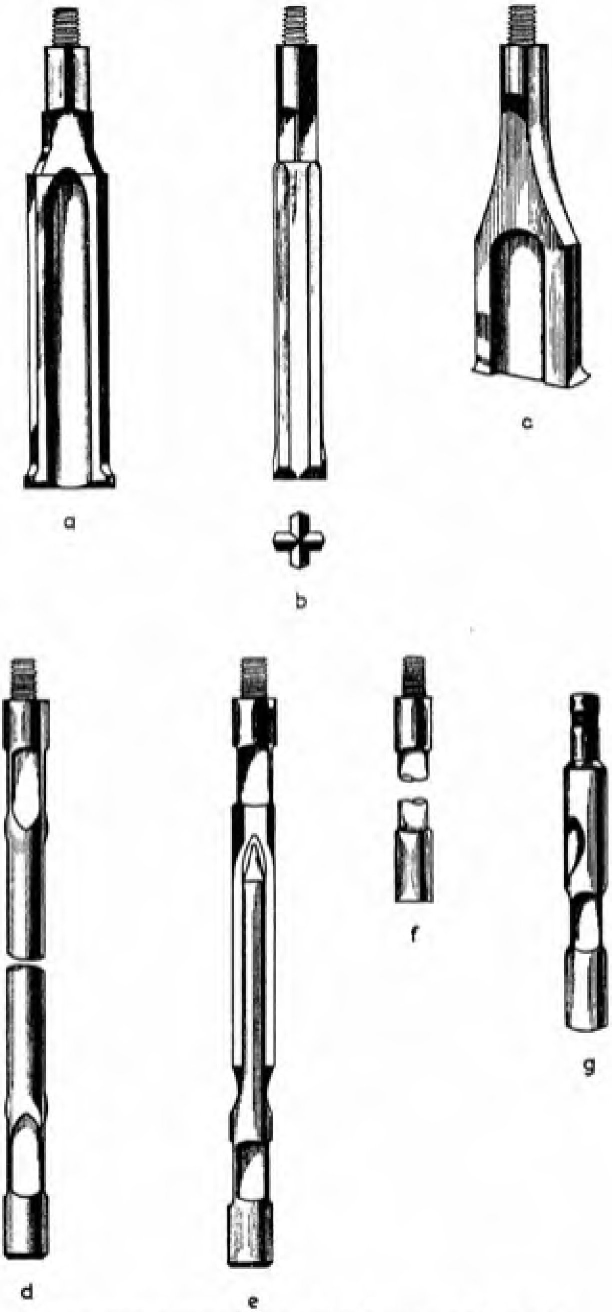


FIG. 127. TOOLS USED IN ROPE DRILLING (CONRAD)

In the second method the cable is wound on the bull-wheel and held by the band brake on this wheel. A short rope is attached from the crank on the band-wheel to a connector or "spudding shoe" on the boring rope just above the bull-wheel. The crank jerks the short rope and this transmits a reciprocating motion through the boring rope to the spudding bit. If the surface beds do not cave until firm rock is reached they are not cased with tubing until this takes place. If they do tend to cave, casing must be inserted before the ground is churned by the spudding bit and then removed by the bailer. The casing is driven by fitting a cutting shoe on the bottom of the first length of tube, generally in 20-ft lengths, which is inserted in a shallow hole dug out by hand. This length is plumbed and then packed solid with earth. The upper end of the pipe is fitted with a drive-head to protect the threads on the end and the pipe is then driven down by a heavy wooden block, raised and lowered by the same means as the spudding bit. As the hole gets deeper additional lengths of casing are screwed to the first and driven down. When firm strata is reached the spudding bit is replaced by a straight or cross bit, *a* or *b* (Fig. 127) 3½–6 ft in length, the auger is screwed on and above this the "jars," *e*, 5½–7 ft in length, consisting of a pair of links which can telescope a distance of 4–12 in. These are used to loosen the bit on the upstroke, the downstroke being free and dependent upon the weight of the bit, auger stem and lower link of the "jars." In order to assist in freeing the bit on the upstroke, the remaining member of the "string," screwed to the "jars" at the lower end and into the rope socket, *g*, at the upper end, is the sinker bar, *f*, 6–16 ft in length. The total weight of the "string" of tools, which is from 33½–81 ft in length, is from 750–11,000 lb. The diameter of the hole drill is from 4–20½ in. with 8 in. as a common size.

The method of reciprocating the string is also changed. The drilling rope of sufficient length for the depth to be drilled is wound on the bull-wheel. The drilling rope is taken over the crown-wheel and the string of tools attached. The crossed rope drive from the band-wheel is thrown off and the string lowered into the hole controlled by a band brake on the bull-wheel. Reciprocation is by means of the walking-beam, *a* (Fig. 126), 26 ft in length pivoted on a fulcrum supported by the samson post, *k*. With the bit resting on the bottom of the hole and a few inches of play in the jars the rope is wrapped with thin rope or marline and gripped by the temper screw, *c*, which is hung on the end of the walking-beam which now takes the weight of the string. Some 20 ft of slack rope is coiled on the derrick floor to prevent lashing of the rope. The other end of the walking-beam is connected by an arm known as a Pitman, *l*, to a crank and wrist

pin on the band-wheel shaft. The engine is controlled by a telegraph line from the headache post, *m*, to the engine throttle.

The temper screw enables the bit to be fed down a distance of 4 ft. In a shallow hole the rope is twisted to prevent the bit sticking, but as the hole gets deeper the twist in the rope is sufficient to prevent the bit striking in the same place. At the end of the travel of the temper screw the slack rope is taken up by rotating the bull-wheel, the rope is unclamped from the temper screw and this is run back, the Pitman is disconnected and the string is wound up by the bull-wheel and swung to the side of the derrick when it reaches the top. The bailer is lowered into the hole and clears out the cuttings. This is drawn up and the string is again lowered into the hole. Reamers of various designs may be used to enlarge a hole already drilled, so that casing above may be carried down to a greater depth or to straighten or clear a hole which has been badly drilled.

If an accident occurs, such as jamming of the bit, breakage or unscrewing of some member of the string, breakage of the rope or sand-line, jamming of the bailer or of casing, loss of casing tubes or equipment falling down the hole, various fishing tools and especially long jars, enabling a strong jerk to be imparted to a jammed tool, are provided. Some of these are standard tools but special tools may have to be designed to deal with the emergency. If the trouble cannot be cleared by fishing, an attempt may be made to break up the lost tool by drilling or by explosives. Alternatively the hole may be diverted clear of the obstruction by filling the bottom of the hole with steel, flints or old steel rope. In addition to the standard rigs, smaller portable rigs working on the same principle but carried by trucks and with a lighter, shorter derrick may be used for holes of less depth (Fig. 128). Combination rigs, enabling the same equipment to be used for either rope or rotary drilling may also be utilized.

The cost of rope boring, as with other systems, is variable as this depends upon the rocks penetrated and the depth attained. Costs of holes between 500 and 3,000 ft averaged 30s per ft pre-war but for deeper holes costs varying from £1–£2 per ft have been recorded.

OIL-WELL DRILLING BY THE ROTARY SYSTEM

This system is adopted to drill more than half the footage required for oil, particularly the deeper holes more than 6,000 ft in depth. Cores of the strata penetrated may be obtained by this method but coreboring is unusual except in pilot holes or at particular horizons and normally the whole of the strata in the hole is reduced to cuttings. These are recovered from the circulating mud flush and form the only evidence of the rocks drilled through, except that their

hardness is related to the weight necessary on the drilling bit to ensure adequate progress. The resistance of the rocks penetrated may, however, be measured and give some index of the type of rock which has been bored. The drilling equipment may be driven by

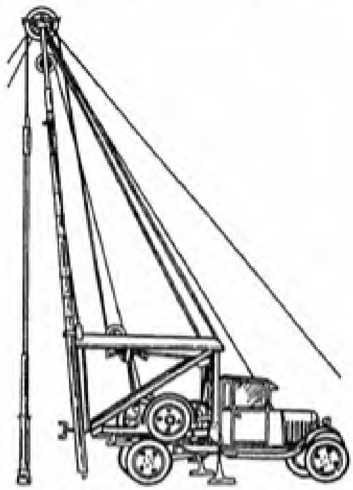


FIG. 128. PORTABLE DRILLING RIG (CONRAD)

steam engines, diesel or gas engines or by electric motors. The horsepower required depends on the depth to be drilled; but two units of 225–250 h.p. are often used and where a diesel-electric combination is used, the Ward-Leonard system of control, similar to that used in winding and on steel rolling mills, may be adopted.

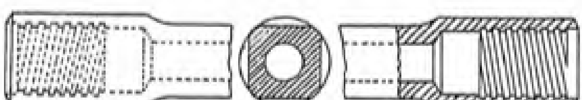


FIG. 129A. KELLY OR GRIEF STEM

Derricks have been standardized in accordance with specifications of the American Petroleum Institute and vary in height from 66–136 ft with bases from 20–30 ft square, but for exceptionally deep wells derricks 175, 185 and even 250 ft high have been used, the cost of these derricks erected, exceeding £2,000. The power is transmitted to the bit by rotating a string of heavy drilling pipe, 3 or 4 in. in diameter in 20–30 ft lengths, down which mud is pumped returning

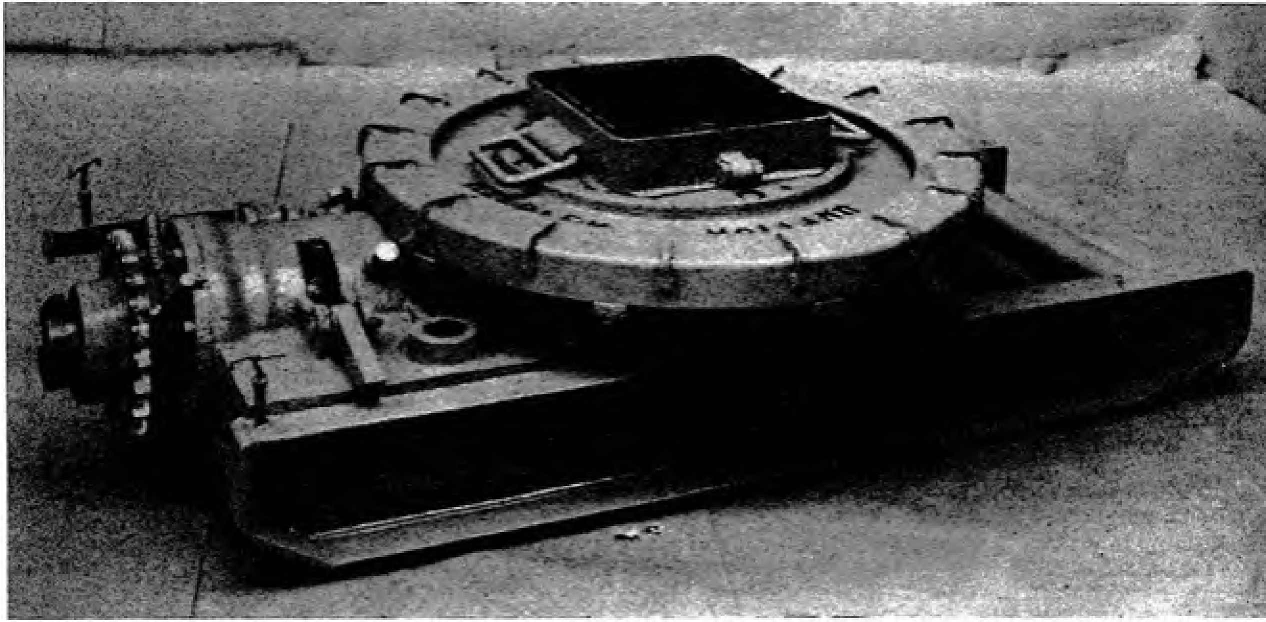


FIG. 129B. ROTARY TABLE

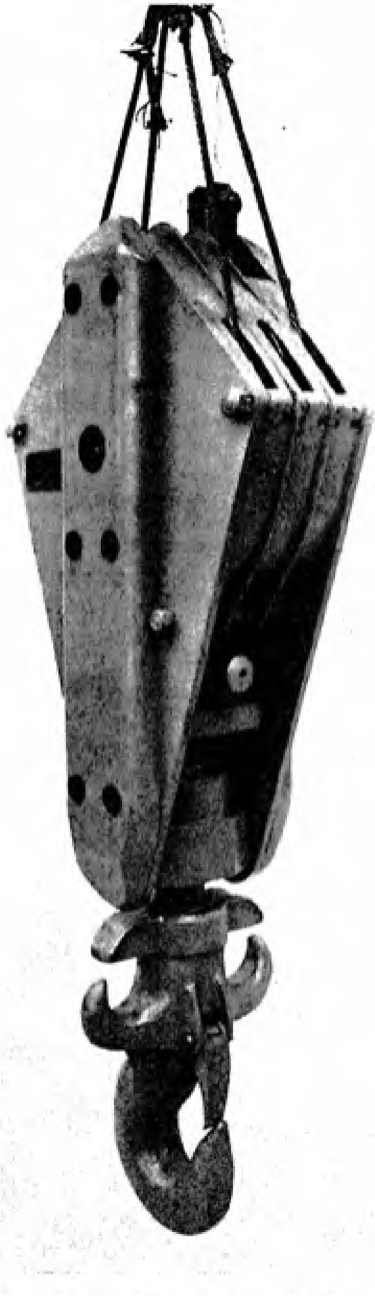


FIG. 129C. HOISTING PULLEY AND HOOK

up the annular space between the pipe and the walls of the borehole. The method of rotating the pipes at speeds up to 300 and even 400 rev/min is by screwing the string to a chrome-nickel steel square shaft from 4 to 6 in. side and 30–60 ft in length, known as a Kelly or "grief stem," (Fig. 129A). The Kelly passes through a square hole in a horizontal bevel gear or rotary table (Fig. 129B) rotated by a motor or engine depending upon the type of power used. The Kelly is

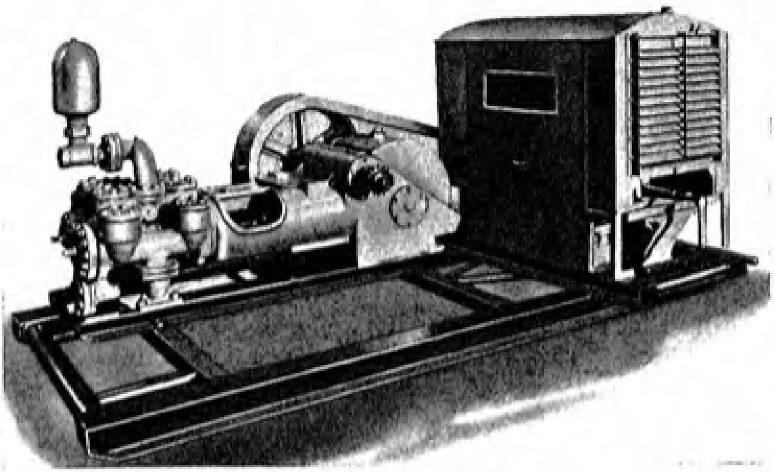


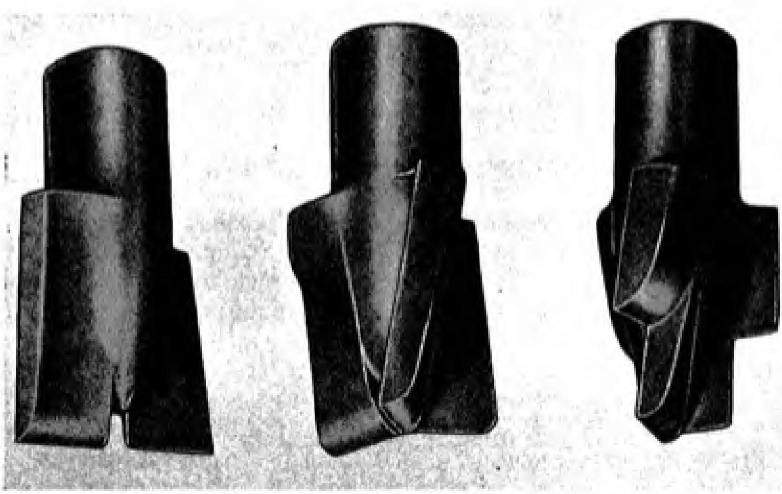
FIG. 130. MUD-FLUSH PUMP (CONRAD)

suspended from a strong hook carried at the base of a hoisting-pulley (Fig. 129C) through a swivel with loose connection to the mud flush pump (Fig. 130). The Kelly can thus slide through the rotary table while this revolves as the hole is bored deeper. The Kelly and string are raised by means of the hoisting rope which is in multiple purchase between the hoisting block and the crown block (Fig. 126A), and is wound on to a hoisting drum known as the draw-works, *e*, chain driven through clutches with three or four gears by a separate engine or motor.

Much attention has been paid in the past twenty years to the design of drilling bits for rotary drilling which vary in diameter from $3\frac{3}{4}$–$9\frac{3}{8}$ in. The design adopted in a particular case depends upon the hardness of the strata drilled. In the softer rocks drag bits (Fig. 131A), with an alloy steel head to which drop-forged nickel-chrome blades, Stellite or tungsten carbide tipped, are welded, or a fishtail bit, B, with replaceable blades are used. In medium hard rocks a Hughes

bit of the roller type with serrated teeth tipped with tungsten carbide on a cone carried on a roller bearing may be adopted. For stronger

(a)



(b)

FIG. 131. ROTARY BITS

strata a three-roller Hughes bit is used and for very hard rocks a Reed roller bit is adopted. The addition of drilling collars to increase the weight on the bit to approximately 1,000 lb/in. of bit

diameter, the magnitude of which is indicated on a dial, enables drilling progress to be increased.

The actual speed of revolution of the bit decreases with increase of depth from 300–125 rev/min. The actual speed of drilling depends to a great extent on the depth as the time required to change bits in a deep hole amounts to several hours and is the factor which has influenced bit design to give the maximum possible life. At shallow depths 160 ft/h has been drilled but at depths from 10,000–15,000 ft the rate may fall to 2 ft/h.

The cost also varies with depth and the hardness of the strata, published cost varies from £2 10s to £6 per ft.

Mud Flush

Mud is used as the circulating medium in the borehole for the following reasons—

1. To prevent blow-outs of gas or oil from the hole by subjecting the strata to a greater pressure than the hydrostatic head corresponding to the depth of the hole.
2. To seal off small feeders of water, gas or oil by forming an impervious layer on the sides of the hole.
3. To cool and lubricate the bit.
4. To convey the cuttings out of the hole and to hold them in suspension when drilling is stopped and prevent them falling to the bottom of the hole.
5. To prevent the sides of the hole caving.

In order to increase the specific gravity of the mud powdered material of high density, barytes or iron oxide, is added and to improve the colloid content, in order that they may "gel" to the right extent (this must not be too low or cuttings are not held in suspension, and not too high or the mud will lack fluidity), Bentonite is added and the mud may also be treated with other chemicals.

In order to remove the cuttings and to maintain the mud in good condition it is screened on vibrating screens of 20–60 mesh before passing to a reservoir from which it is recirculated. As the mud is subjected to a pressure of many thousands of lb/in.^{2} at the bottom of a deep hole, any gas entrained will expand as it ascends and reduce the weight and pressure exerted by the mud. This may cause a blow-out which may be prevented by de-gassing the "gas-cut" mud by subjecting it to a vacuum process. As the success of the drilling operations depends to a large degree on the proper condition of the mud flush, great pains are taken to keep it in the best possible condition and to this end careful testing of the viscosity and other physical properties is carried out.

Recovering Cores

In both rope and rotary drilling, cores may be recovered of any particular section of the strata desired, this giving much more accurate information than that obtainable from the cuttings alone. In rope boring a special core bit and a core barrel is used in place of the normal bit. In rotary boring three types of core bit are available. To receive the core a core barrel which revolves with the drilling pipes or a double core tube may be adopted. The latter has an inner barrel which does not rotate, thus reducing abrasion of the core and leading to a higher percentage of core recovery.

The retractable type of bit is similar in construction to the standard types of rotary bit arranged to cut a full-size hole, but it is fitted to an outer core barrel and designed to leave the central portion of the strata undrilled. A core barrel with a coring bit is dropped down the drilling pipes and locks itself to the outer bit. Core from $1\frac{1}{4}$–$2\frac{1}{2}$ in. in diameter is drilled and recovered in the inner core barrel which is picked up when full by an overshot dog on a thin wire rope and wound to the surface without withdrawing the normal drilling string of pipes from the hole. If further cores are not required an inner drilling assembly is dropped in place of the core barrel when the entire area of the hole is drilled to cuttings.

The cost of coring varies from 15s to 31s 6d per ft for rope drilling, with 22s as an average while 9s per ft is an average cost of coring with rotary drilling, the speed of revolution being reduced when coring to 50–75 rev/min. The costs quoted are on a pre-war basis when costs were much more stable.

CONRAD COUNTERFLUSH CORING SYSTEM

This method of obtaining a continuous core record of the strata penetrated was first used by Fauck in percussive boring with hollow rods and a flushing system circulating in the reverse direction to that normally adopted. It has since been applied by the Conrad Company of Harlem to the rotary system of drilling and the notable feature is the provision of a reversed mud flush circulation which permits of uninterrupted core recovery. The surface casing, *A* (Fig. 132), through which drilling proceeds, is cemented in place and provided with a stuffing box or blow-out preventer, *B*, and the delivery from the mud flush pump is connected to a tee immediately beneath. The mud flush passes under pressure down between the casing and the drilling pipe-string and then up through the coring bit, *C*, and the drilling pipe-string through the swivel head, *D*, to the core evacuation hose, *E*, and the core receiver and sludge-pit. When successive

lengths of casing have been inserted in the hole the connection between each is by a casing head and a stuffing box. No core barrel is employed and the drilling pipes are flush inside. Cores and cuttings are forced upwards through the drilling pipes and the swivel head by the ascension of the mud flush under pressure. Thus all cores and

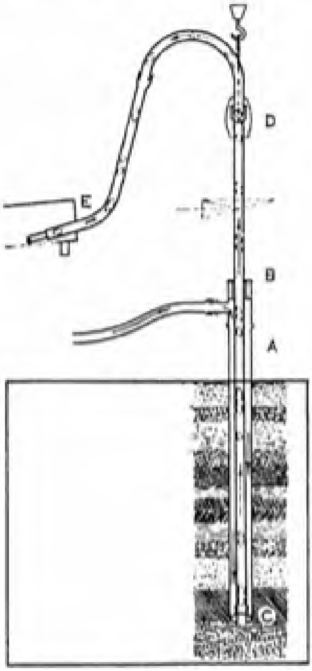


FIG. 132. CONRAD COUNTERFLUSH CORING SYSTEM

cuttings are recovered at the surface within the short interval required for their ascent so that a record of changes in the strata is obtained practically simultaneously with their penetration in the hole. As no core barrel is used there is no necessity to stop drilling to unscrew the pipe-string to recover core and then screw on and lower the string again. This is only necessary when the bit needs to be changed which may only be after 500 ft of drilling in the softer rocks which may take a week to drill.

Deflection of Boreholes

It is often advantageous in a number of circumstances to deflect a borehole. This may occur when broken tools or casing cause a jam

in the hole and the latter can only be continued if deflected, to drill into strata on the other side of a fault, or to drill into minerals lying under surface water.

Several methods have been developed to enable the deflection to take place in a controlled manner provided the operation is checked

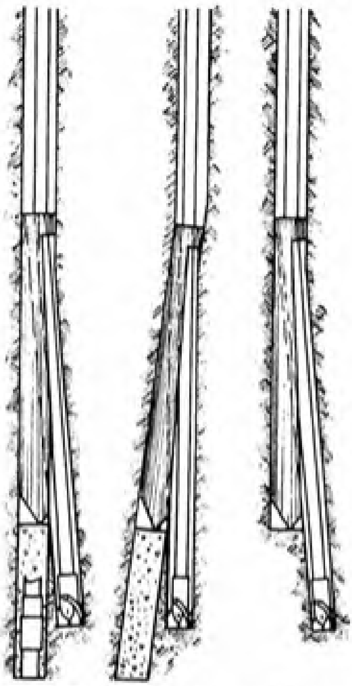


FIG. 133. EASTMAN REMOVABLE WHIPSTOCK

at frequent intervals by borehole surveys. Fig. 133 shows the use of the Eastman removable whipstock for this purpose. It consists of a wedge-shaped chrome steel appliance some 10 ft in length with a tapered groove on the side to which deflection is desired and is fitted with a sharp anchoring toe to prevent displacement when lowered into position. The top is fitted with a collar, which fits loosely on the drilling string, but is less in diameter than the drilling bit and so is withdrawn when the string is lifted. The deflection thus, started is increased by the use of special bits; further whipstocks may be required successively to accomplish the degree of deflection required.

Alternatively a "knuckle-joint" (Fig. 134), may be attached to the

drilling string to which is fitted a diamond centre punch which starts a smaller hole deflected about 5° from the axis of the vertical hole. The punch is used percussively at first by raising and lowering the drilling pipe-string and this is then rotated until about 20 ft of the deflected hole is bored. The punch is then replaced by a small size

FIG. 134. KNUCKLE JOINT (EASTMAN)

rotary bit which continues the deflected hole. Next, the hole is reamed out to full size and continued with a full-size bit, the flexibility of the pipe-string being sufficient to negotiate the bend in the hole.

When deflection is required at an intermediate point in a borehole which is cased, a Casing Whipstock is used which is lowered on the drilling string to the selected point and there released. It contains a deflecting wedge, and a milling cutter is substituted for the bit to cut

through the side of the casing. The hole is then continued in the new direction using the normal drilling bit.

If the hole is uncased a Hydraulic Bridger may be used which has two arms that penetrate into the sides of the hole when released at the selected point, and anchor the sealing plug in position. A deflection wedge or whipstock is then placed upon the plug and the hole is deflected.

In the Hall-Rowe method of deflection applied to diamond boring, the vertical hole is plugged at the point of deflection by a dry wooden plug which is swelled firmly into position by treating with water. A drive wedge, with a sharp-pointed foot with a hydrofluoric acid clinometer above, is dropped on to and penetrates the wood plug. After some 30 minutes the clinometer is detached and withdrawn to the surface. From its etched line the position of the pilot wedge in the hole can be computed. A long deflecting wedge, with a pilot wedge beneath arranged to fit in one position only on top of the drive wedge when rotated, is then lowered. The long deflecting wedge is thus orientated in the desired direction; when in position a copper rivet is sheared and the drilling string can be withdrawn leaving the wedge behind. The ring, by which the wedge was attached to the string, is then ground off, by means of a rose bit which is withdrawn, and a $\frac{11}{16}$ in. diamond core bit and core barrel substituted. The long wedge has a tapered groove sufficient in width to take the diamond core bit and barrel, which then bores the initial short length of the deflected hole. When this length is completed the $\frac{11}{16}$ in. bit and barrel are withdrawn and the wedge and the pilot hole are reamed out to full size by a diamond reaming bit. When reaming is completed diamond boring at full diameter proceeds in the new direction.

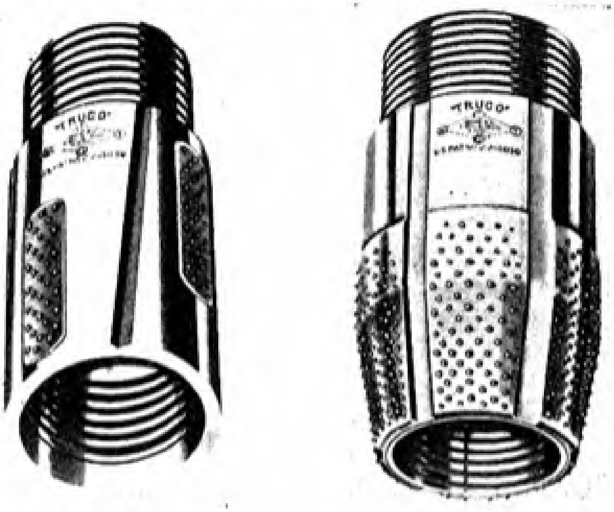
The deviation of the borehole is controlled by varying the flexibility of the joints above the bit, the weight on the bit, and the speed of rotation. The total deflection obtained may approach 60° and the cost was generally about £500 pre-war.

Diamond Drilling

This is the method of drilling which gives the most positive evidence in the form of cores of the strata drilled through; it thus forms a most useful tool in confirming or otherwise the presence of minerals, including coal seams, the probability of whose occurrence has been determined by prospecting. The method is widely adopted all over the world both for exploration from the surface and from underground workings, similar appliances being adopted in both situations. Diamond-drilled holes, along with those drilled by other rotary methods, are likely to deviate more widely from the vertical than those

drilled by percussive methods. On the other hand holes can be drilled with equal ease in any direction and diamond drilling rigs are usually equipped for this purpose.

The diameter for diamond drilled holes is generally much less than those bored by other methods, the standard sizes of drilling pipes used being $\frac{5}{16}$ in. (*E*), $1\frac{5}{8}$ in. (*A*), $1\frac{29}{32}$ in. (*B*) and $2\frac{3}{8}$ in. (*N*), giving cores of $\frac{7}{8}$ in., $1\frac{1}{8}$ in., $1\frac{5}{8}$ in. and $2\frac{1}{8}$ in. respectively in diameter.



(a) (b)

FIG. 135. REAMING SHELLS (SULLIVAN)

Corresponding casing diameters are (outside diameters)—$1\frac{13}{16}$ in. (*EX*), $2\frac{1}{4}$ in. (*AX*), $2\frac{7}{8}$ in. (*BX*), and $3\frac{1}{2}$ in. (*NX*) the corresponding inside diameters being $1\frac{1}{2}$ in., $1\frac{29}{32}$ in., $2\frac{3}{8}$ in. and 3 in. Cement grout is however being adopted to an increasing degree to support boreholes which tend to cave in place of steel casing. The hole is drilled and cored into the tender ground as far as considered safe. The grout is then pumped down the boring rods or lowered in a bailer and the hole in the caving ground is filled, a quick setting cement being used. After setting, the cement plug is drilled through as if it were normal strata and the drilling is continued as far as is safe into the strata below from which further cores are recovered. When the safe limit is again reached the hole is again grouted. This method is somewhat cheaper than casing which generally entails reaming out the hole to a larger diameter. Alternatively a cutting shoe, set with small diamonds (Fig. 135), may be attached to the string of casing

pipe and rotated. This acts as a reamer. Grouting has the additional advantage that it allows successive tender horizons to be supported without reducing the hole diameter entailed in cased holes starting with a larger initial diameter. The minimum size of core usually adopted in coal-bearing formations is 2 in. diam, in harder formations a smaller diameter gives adequate core recovery.

BITS FOR DIAMOND DRILLING

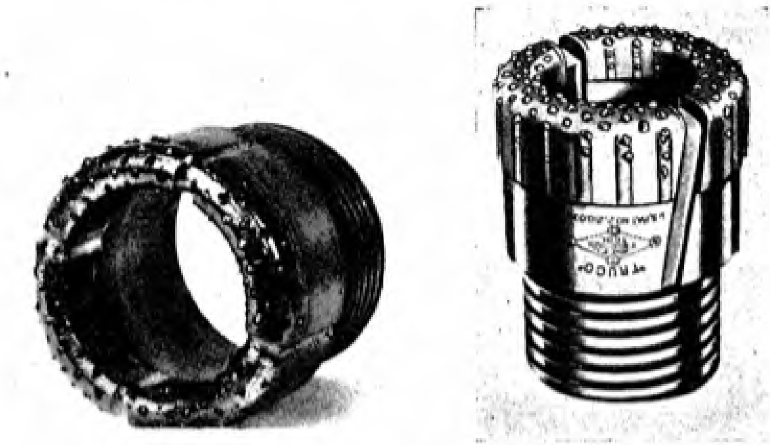
In this system the drilling is done by various grades of industrial diamonds set in a blank or collar (Fig. 136) screwed to the bottom of the core-barrel. Blanks with a rounded shoulder are now most commonly used although square-shouldered blanks may be adopted in softer rocks and a solid bit, taking no core, may be used in rocks such as those of the Mesozoic Age, of which information is not required. Alternatively these may be drilled by quicker and cheaper percussive methods.

Slots are cut in the base of the blanks to convey water to the cutting face. The size and number, and method of inserting and securing the diamonds in the blank, varies with the speed of revolution adopted, with speed of drilling and with the type of strata being drilled; but they must always be arranged, like the picks in the chain of the coal-cutter, so that the whole annular space between the core and the side of the hole is abraded by contact with a diamond every revolution, and adequate side clearance must be provided for the bit and the core-barrel. Care must be taken that the metal of the blank does not come into contact with the rock or it will be worn away with loosening and possible loss of one or more diamonds; which is an expensive accident.

The types of diamond used are white or tinted brilliants crystalline in shape, bort or impure crystalline diamond generally from South America and brown in colour and "carbon" composed of very small crystals of diamond together with amorphous graphite, black in colour. The number and size of the diamond set in a blank varies considerably. Formerly popular was a setting with eight relatively large diamonds, four outside and four inside, the weight of the stones totalling about 16 carats. This arrangement is still used in the square-shouldered bit shown which is adopted in softer rocks. The more usual round-shouldered blank set with a large number of small stones, from 40 to 100 depending on the diameter of the hole and weighing 1/5 to 1/20 of a carat each, gives more even wear and higher drilling speeds.

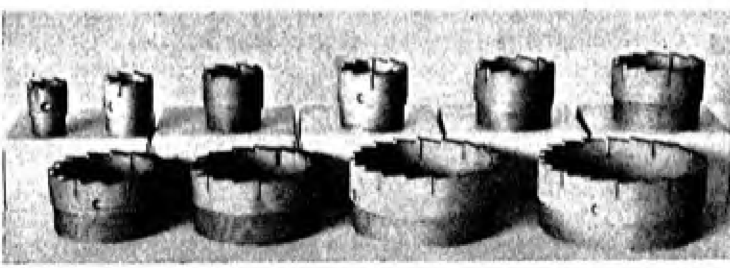
Cavities are cut in the blank to the shape of each particular diamond, which is held in position by copper or white metal carefully

tamped round the diamond by a light hammer and punch so that it projects about $\frac{1}{64}$ in. from the blank. Setting diamonds is a skilled and laborious job and moulded bits are being used to an increasing



(a)

FIG. 136A. BITS FOR DIAMOND BORING (SULLIVAN)



(b)

FIG. 136B. SAW-TOOTH BITS (SULLIVAN)

extent. In this method the small diamonds are placed in a mould and molten white metal is run in round them, "finehards" bit (Fig. 136A). In the Kobelite bit metal powder is used to hold the stones and the whole is then pressed or sintered into strip inserts or discs which are brazed to the blank.

The Sulset bit (Fig. 136A) is moulded into ridges into which small borts are sintered. The valleys between the ridges allow the cuttings

to be removed quickly from under the bit. Crushed bort 30–40 carats in weight mixed with iron powder may also be moulded into the form of a ring $\frac{3}{8}$ in. thick sintered and then soldered to the blank. Bits with a large number of small diamonds last much longer than those with a smaller number of larger diamonds and also drill about 50 per cent faster, a higher speed of rotation of 1,000 rev/min being adopted. For maximum core recovery drilling is at slow speed with heavy pressure on the bit in hard rocks and at high speed with light pressure in soft rocks.

Core recovery is greater in deeper holes than in shallow loose strata. In the deepest holes drilled in South Africa to a depth of

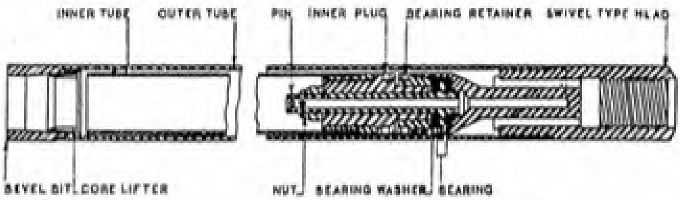


FIG. 137. DOUBLE-TUBE CORE-BARREL FOR COAL (SULLIVAN)

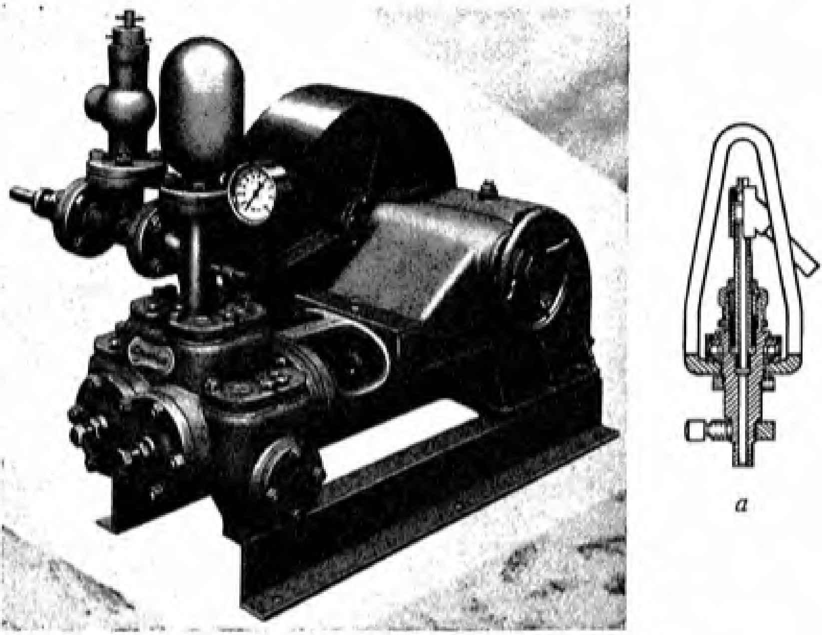
7,000–10,000 ft with cores $1\frac{3}{8}$–$2\frac{1}{8}$ in. diam core recovery ranged from 92 to over 97 per cent, the cost per foot drilled averaging between £2 16s and £3 16s, the deepest hole being the cheapest. The average rate of drilling attained for these depths was 22 and 31 ft per day. In the Orange Free State the contract price for holes 6,000 ft deep was £2 per ft. For softer rocks artificial diamonds, "thoran," may be used or hard metal inserts of Widia (tungsten carbide) or stellite, or saw tooth and fishtail bits, face-hardened with "borium" or stellite (Fig. 136B).

Cores

Above the bit comes the core-barrel of which three types are used—single tube, rigid double tube and double tube with stationary inner tube. The first facilitates core removal and speed of drilling, the second conducts the water from the drilling pipes between the double core-barrels and prevents erosion of the core, while the third, in which the inner barrel is mounted on ball bearings (Fig. 137), and does not revolve, reduces both erosion and abrasion of the core and is practically invariably used when boring for coal and in other friable strata. The hole is also of larger diameter in these cases, 2-in. cores being the minimum size adopted for coal seams. Core-barrels vary in length with the capacity of the drill from 20 in., 2 ft, 5 ft, 10 ft,

20 ft, and, exceptionally, longer barrels may be used. In uniform rocks the longer the core-barrel used the greater the speed of drilling as the number of times the pipes are hoisted out of the hole, core removed and pipes again lowered, is reduced and this takes between 9–10 hours when the hole is 6,000 ft deep.

The core is broken off and gripped by a core-lifter of the split-ring



a

FIG. 138. WATER FLUSH PUMP AND WATER SWIVEL (CRAELIUS)

taper type. This slides over the core as it ascends into the core-barrel but on raising the barrel the lifter grips the core firmly and breaks it off.

The drill rods are supplied with water by a pump (Fig. 138), through a water swivel, *a*, screwed to the top of the string. The quantity of water required depends on the diameter of the hole, the hardness of the strata and whether or not it is fissured, when water is lost, or whether the water is settled and re-used. In order to convey the cuttings away from the bit and maintain the speed of drilling a certain velocity of water current is required in the annular space between the pipe-string and the side of the hole. This is generally from 60–90 ft/min unless drilling in hard materials such as galena

(lead sulphide). This requires from 2–25 gal/min depending on the diameter of the hole. The velocity is higher past the core and in soft rocks may erode the core. In such cases either a double core barrel is used or the water supply is cut down. The latter course, although it increases core recovery, reduces speed of drilling.

A split-core tube has recently been introduced in the South Yorkshire coalfield which gives some 98 per cent recovery of coal

FIG. 139. DRILL RODS AND COUPLINGS (SULLIVAN)

seams. By placing a properly designed metal trough over the core in its half-tube and inverting it, the core can be transported exactly as recovered for examination without being broken by being forced longitudinally out of the core barrel.

Driving and Feeding Mechanism

Motion is imparted to the bit through cold-drawn seamless steel tubes in 2, 5, 10 or 20 ft lengths. These pipes are screwed and socketed and connected by screwed couplings (Fig. 139). They are raised from and lowered into the hole by means of a hoisting drum (Fig. 140), geared to the driving shaft of the main driving engine through a clutch which is disengaged when drilling. Multiple driving speeds are generally provided by variation of the gear ratio between the engine and the drum.

The derrick carries the crown pulley over which the hoisting rope passes, and this is generally a tripod about 22 ft in height for shallow holes drilled to a depth of 600 ft, and for deeper holes is a steel derrick allowing tubes to be changed in 40 ft lengths (Fig. 141).

The main driving engine may be steam driven but is usually electric, petrol or heavy oil (diesel) driven. For shallow holes less than 400 ft in depth the drill may be hand-operated. Underground

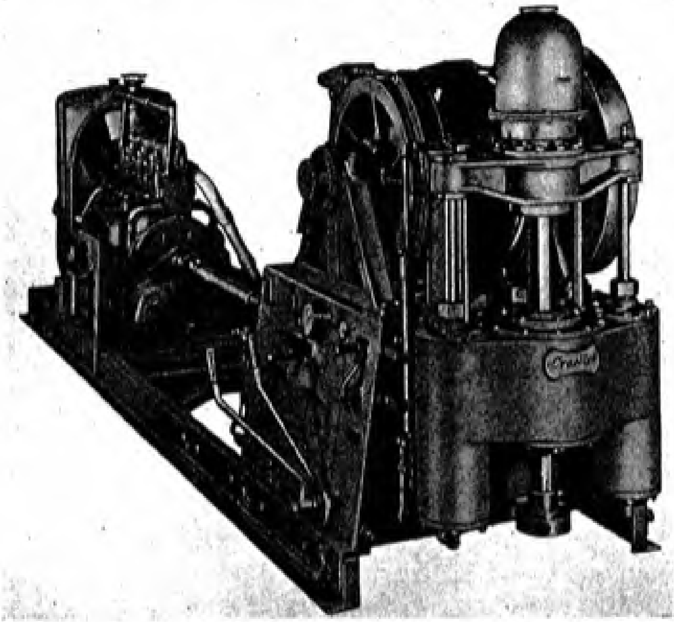


FIG. 140. DIAMOND-DRILLING DRIVING MECHANISM, 6,500 FT CAPACITY (CRAELIUS)

drills may also be operated by hand or by a compressed-air driven turbine. High drilling speeds, with corresponding increased rotational speeds, have influenced the provision of ball bearings and grease-gun lubrication throughout.

The feeding mechanism is contained in the swivel head; so named, because it can be swung to one side clear of the hole to allow the drilling pipes to be raised from it, to unload the core-barrel or change the bit, and it also allows drilling to take place at any angle to the vertical. The feeding mechanism is either of the differential screw type or the hydraulic type. The former (Fig. 142), consists of a main screwed spindle, *A*, carrying the chuck which engages the drilling

rods by means of studs. The spindle is rotated by the splined shaft, *B*, with which it turns but can move up or down. The splined shaft

FIG. 141. HIGH STEEL DERRICK (CONRAD)

is rotated by and keyed to the bevel wheel, *C*, which is driven from the main driving engine through a second bevel wheel at right angles. On the splined shaft below the bevel wheel is keyed a straight cut

gear wheel, *D*, which drives a second gear, *F*, keyed to a counter-shaft, *E*. At the upper end of this counter-shaft are three gears, *G*, one above the other, which mesh with three corresponding gears, *H*, keyed to a feed nut, *I*, threaded on the screwed spindle, *A*. The three gears, *G*, and *H*, give different feed ratios and one or other of them may be engaged by the sliding key, *J*, with two neutral positions

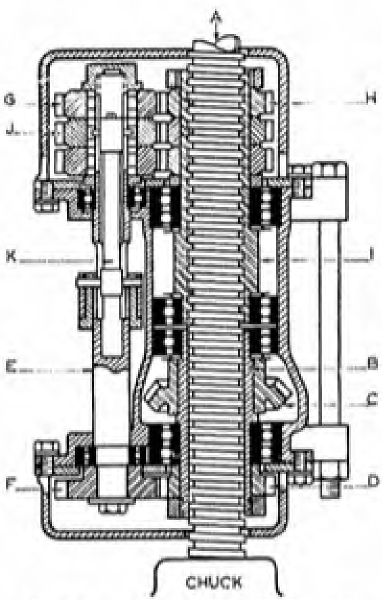


FIG. 142. SCREW FEED OF DIAMOND DRILL (SULLIVAN)

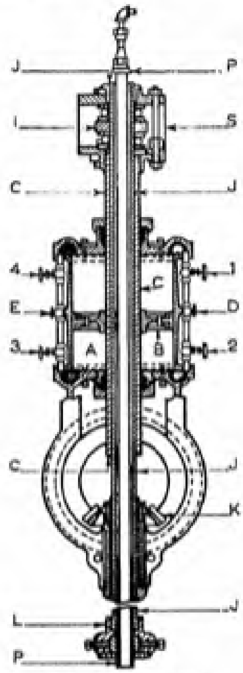


FIG. 143. HYDRAULIC FEED FOR DIAMOND DRILL (SULLIVAN)

between. The key is carried by the shaft, *K*, sliding inside the counter-shaft, *E*, and is moved by means of a hand-wheel, thus giving three speeds and two neutral positions which vary according to the gear ratios adopted between 50–1,300 rev/min, 200, 400 and 600 rev/min in. of feed being often adopted.

Screw feeds are generally adopted on the smaller capacity machines and they give a constant rate of feed depending on the position of the hand-wheel and consequently a varying pressure on the bit depending on the hardness of the strata being drilled. This is valuable information to the driller and of the geology of the strata.

But the speed must be reduced in soft strata as the bit may emerge from this suddenly into hard strata and damage the diamonds.

On the large-capacity machines, therefore, the hydraulic feed (Fig. 143), is generally adopted, as this gives a constant pressure on the bit, the rate of feed varying with the hardness of the strata drilled. If a cavity is met in the hole the danger of damage to the bit is reduced as the hydraulic piston then supports the drilling pipes. The rate of speed is infinitely variable while that of the screw feed is limited to three speeds unless the gear ratios are changed.

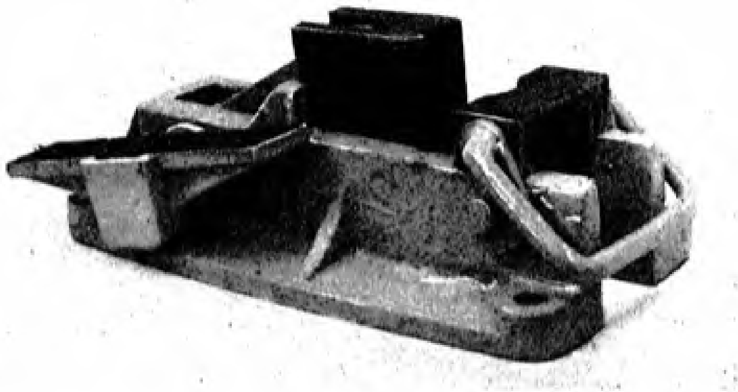
The hydraulic piston, *B*, works in the cylinder, *A*, which is shown single in the model illustrated although twin cylinders are adopted on the large-capacity drills. The piston rod, *C*, is hollow and as it is moved up or down by the piston it communicates this motion through the roller friction head, *S*, to the collar, *I*. This is fixed to the drive pipe, *J* (Fig. 143), which is rotated by the bevel wheel *K*, driven in turn by the bevel pinion on the main engine driving shaft. The drilling pipes *P*, pass through this drive pipe and are gripped by the chuck, *L*, and thus are rotated and raised or lowered. The feed up or down is obtained by raising or lowering the piston, *B*, by opening one of the inlet valves, 1, or 2, communicating with the high-pressure water pump and opening one of the outlet valves, 3 or 4. Thus by opening one pair of diagonally-placed valves the piston is raised or lowered. The rate of feed is varied by adjusting the amount of opening of the valves and the pressure on the bit is indicated on a pressure gauge. The whole feeding and driving mechanism is mounted on a skid.

Drilling Operations

Drilling generally takes place through a stand-pipe which is spudded into solid strata in a similar manner to that adopted in oil-well drilling. The stand-pipe prevents loose surface strata falling down the hole and ensures the return of the flushing water to the surface. Placed on top of the stand-pipe is the safety-clamp (Fig. 144A), used to grip drilling pipes or casing when these are being screwed (or unscrewed) to prevent the remainder falling back down the hole and having to be recovered.

When recommencing drilling after changing the bit or emptying the core-barrel the feed mechanism will be clear of the hole. The bit screwed to the core-barrel and to one length of tube is attached to the hoisting-swivel and lowered into the hole with a few inches projecting through the safety clamp. This is gripped by the wrenches and the safety clamp (Fig. 144), and the hoisting-swivel is unscrewed and screwed to a length of drilling tube, the length depending on the

height of the derrick adopted. These are lifted by the hoist and swung over the safety clamp and screwed to the tube projecting from the hole, the whole then being lowered by releasing the safety clamp and controlled by the brake on the hoisting drum until again only a few inches project when the safety clamp is reset. This operation is repeated until the bit is within one drill pipe length of the bottom of the hole. The feed mechanism is now swung into the drilling position over the hole with the feed at the top of its travel. The combined

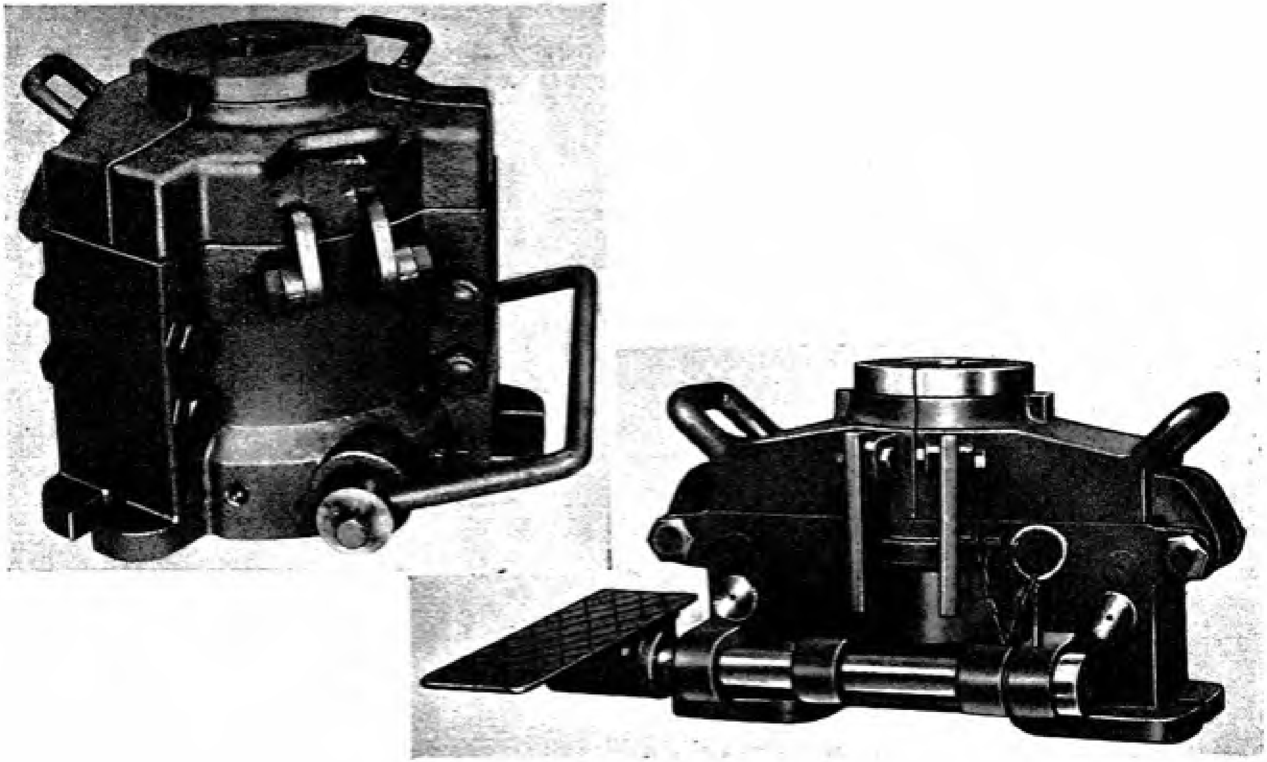


(a)

Fig. 144A

water swivel and lifting bail, *a* (Fig. 138), is screwed to the remaining drilling pipe and this is lowered through the drive pipe, *J* (Fig. 143), and the pipe is screwed to the remainder of the string. The chuck *L*, is now tightened on the pipe and the water swivel connected to the flushing pump (Fig. 138). The safety clamp is released and the pump and drilling engine started, the string being fed down until increased pressure indicates that the bit is on the bottom when the speed is adjusted.

In bringing the string out of the hole the order of operations is reversed. Jamming of the string through caving of weak strata may sometimes be avoided by reversing the direction of feed while continuing to pump water down the drilling pipes; sometimes extra water may assist. Continued flushing when the drilling pipes are raised or lowered is also advisable in fissured strata, as sludge may lodge in the fissures and be driven out into the hole when water circulation ceases.



(b)

FIG. 144B. SAFETY CLAMPS AND ROD HOLDERS

Drilling Accidents

The drilling string or a string of casing may separate in the hole through breakage of a pipe, unscrewing or stripping of the threads. If unscrewed they can often be screwed together again, if not, in the case of stripped or broken pipes, an inside, A (Fig. 145), or outside, B, tap (Fig. 146), is lowered on the upper pipes to cut a thread on the top pipe of the missing string. If this fails a spear, C, is used. D is a core-barrel fishing tap.

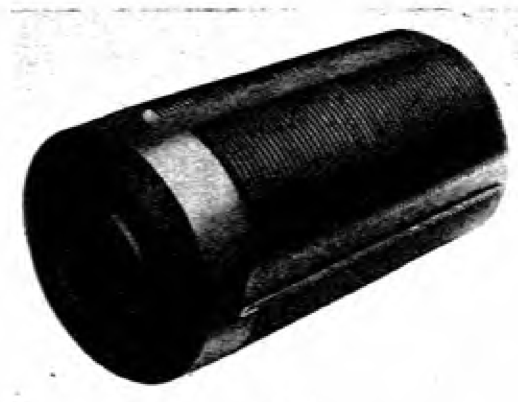
It is important that the bit be gauged frequently so that the hole is drilled full size or jamming may occur and, in addition, diamonds may become detached and lost. If the bottom of the hole is clean an old bit waxed underneath may be lowered on the drilling string and the lost diamond embedded in the wax. If the hole has cuttings in the bottom a bailer with an upper and lower wire mesh clack is lowered on the string, the direction of flushing water is reversed and the diamond and cuttings washed into the bailer which is then hoisted to the surface.

An even more disastrous occurrence is the detachment through breakage, stripping or unscrewing of the complete bit. It may be fished for with taps and even an electro-magnet has been lowered to attempt to pick it up. A larger bit has been used to force it and the strata immediately below into a larger core barrel which entails first reaming the hole. If it is not recovered the hole is generally diverted but the loss of time in fishing, cost of bit and diamonds and of deflecting the hole may greatly increase the ultimate cost.

Chilled Shot or Calyx Boring

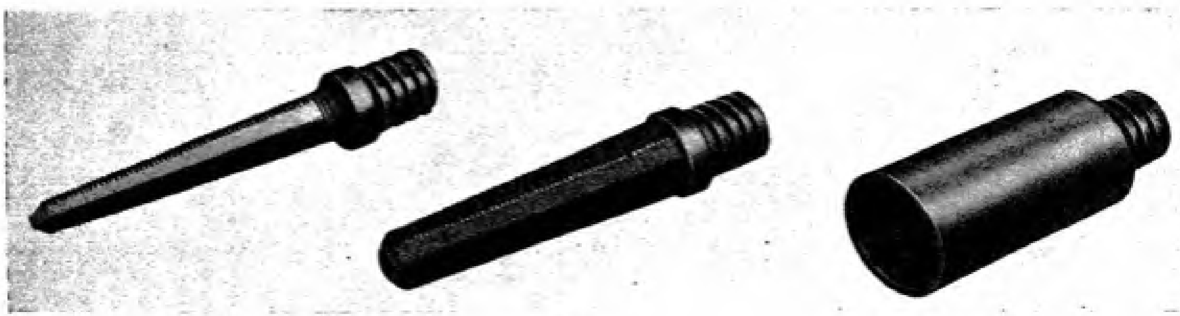
The equipment used in this rotary method of boring is similar to that used in diamond boring with the exception that chilled shot up to $\frac{1}{8}$ in. in diameter is washed down with the flushing water under a blank bit (Fig. 147*A*), to abrade the annular cut round the core instead of using diamonds. This reduces the cost but at the expense of core recovery. Above the core barrel is screwed a calyx-tube (Fig. 147), into which cuttings and sludge are deposited where the water velocity slackens as the area is increased at the top of the calyx-tube, which thus contains a reversed record of the strata drilled. The core is gripped and broken off by dropping sharp gravel into the descending flushing water and care should be taken that this is sharp and that enough is used to get a good grip between the barrel and the core or the latter may fall back down the hole when hoisted.

Holes can be drilled of large diameter by this method and staple-shafts (winzes), 6 ft in diameter have been sunk by this method in



(A)

FIG. 145. FISHING TOOL: INSIDE TAP



(B) (C) (D)

FIG. 146. FISHING TOOLS

Germany and in the U.S.A. In such large holes the weight of the string gives sufficient pressure on the bit; in smaller holes a rack feed is used. The speed of revolution is much less than with the diamond method, generally between 50–100 rev/min. In softer rock a Davis bit, with saw teeth suitably forged to give adequate inside and outside clearance, may be used.

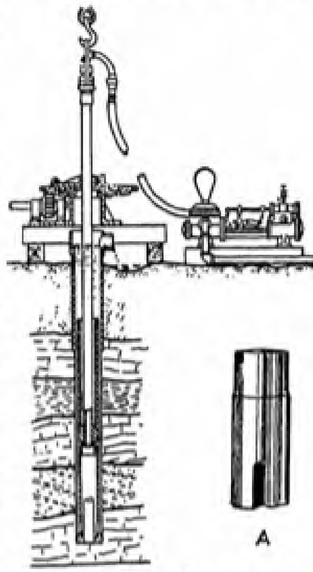


FIG. 147.
CHILLED SHOT OR CALYX BORING
A. Chilled-Shot Bit.

Raky and Similar Systems

Where holes are not required to reach depths of more than a few thousand feet lighter equipment may be used and boring rigs of this type are known as "slim-hole" systems.

The Raky system has been used fairly extensively on the British coalfields to reach depths of 3–4,000 ft. It is a percussive method and so has the advantage of drilling a vertical hole with little deviation and is also easily converted to a rotary core-boring system. In this system 2 in. drill pipes with tapered threads and the ends thickened up are used in conjunction with a heavy chisel, stellite faced, and a mud flush with a specific gravity of 1·4 is circulated down these pipes and returns between the pipes and the sides of the hole or the casing if this is required for support.

In order to increase the speed of drilling a relatively large number of strokes, 80–120 per min, of short length, 3–12 in., are imparted to the pipes by means of a "walking beam" suspended from the boring frame by a system of 30 or 40 springs, *a* (Fig. 148). By this arrangement the inertia of the drilling pipes is reduced allowing a greater number of strokes per minute without setting up heavy vibration which would lead to breakage of equipment. The feed is controlled by three clamps on the drilling pipes supported on the end of the "walking beam" through which the drilling pipes pass. By slackening the clamps the feed is increased and the rotation of the pipes is produced by turning the clamps by hand.

The change to the rotary system is by the substitution of a rotary table running on ball or roller bearings, driven by a bevel pinion on the same shaft as a belt wheel rotated by the main engine. The

rotation of the pipes is by two vertical rods fixed to the rotary table and engaging a clamp on the pipes.

The feed is controlled by a handwheel which engages a plate clutch

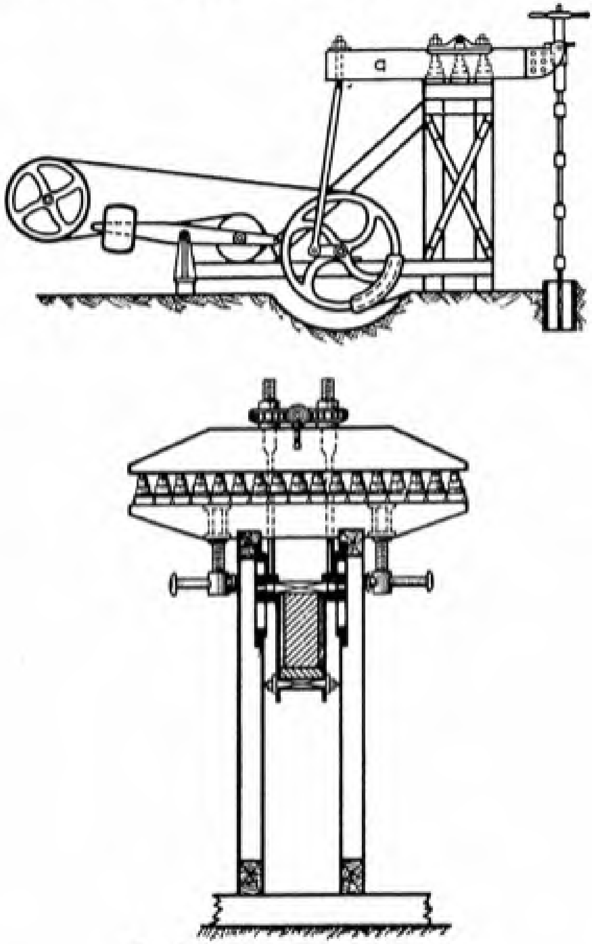
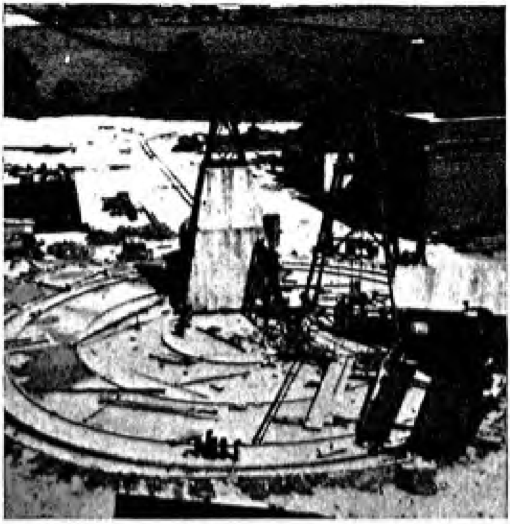


Fig. 148. Raky System of Boring

A. Cross-section showing springs.

and pays out rope by which the drilling pipes are suspended from the hoisting drum. A counterbalancing system is used to balance the weight of the rods and enable them to be lifted if necessary to prevent damage to the diamond bit which is generally used for rotary boring although chilled shot may also be used.



Concentric rail tracks for boring derricks at a shaft being sunk by the freezing system

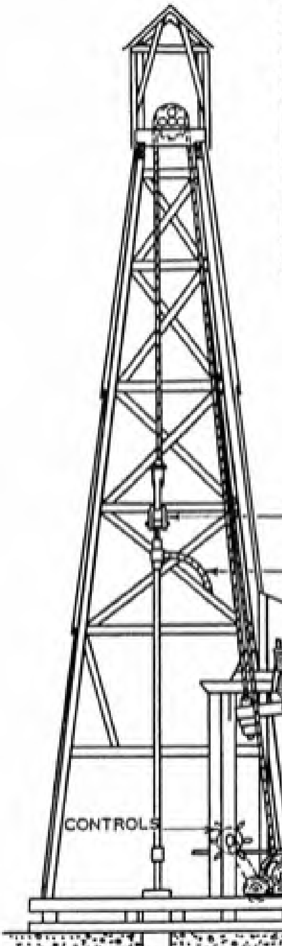
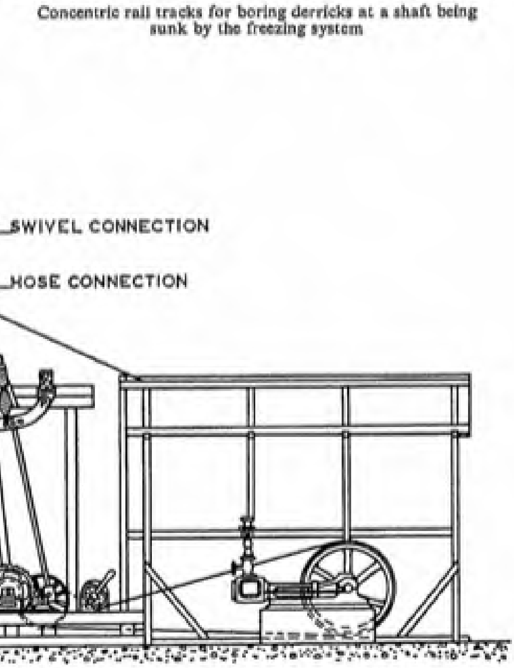
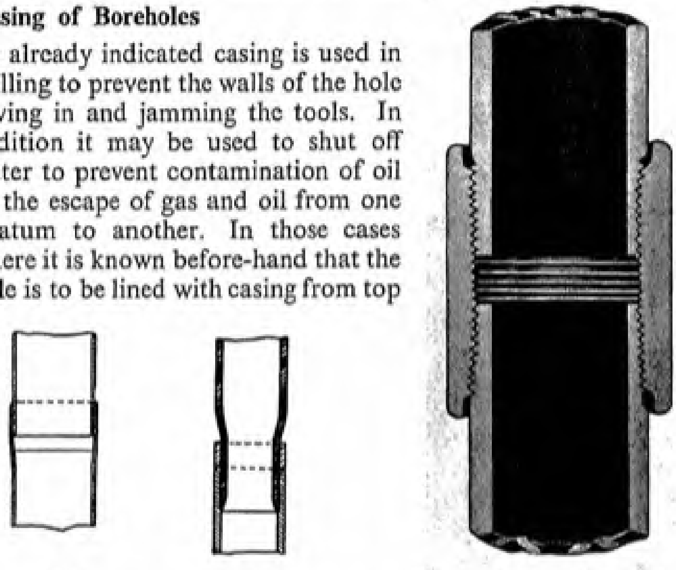



FIG. 149. PERCUSSIVE BORING SYSTEM USED WITH FREEZING METHOD OF SINKING

In drilling holes in connection with the freezing system of shaft-sinking a similar method of percussive boring is used. The derrick moves round the periphery of the shaft on circular rail tracks (Fig. 149), concentric with the shaft, to facilitate easy movement from hole to hole. The drilling pipes are also in this case 2 in. diam with a clear water flush. The initial diameter of the holes is 8 in. for 300 ft and then 6 in. for the remaining depth, in one case 235 ft, and the maximum permissible deviation is 1°. The pipes are turned by hand.

Casing of Boreholes

As already indicated casing is used in drilling to prevent the walls of the hole caving in and jamming the tools. In addition it may be used to shut off water to prevent contamination of oil or the escape of gas and oil from one stratum to another. In those cases where it is known before-hand that the hole is to be lined with casing from top to bottom, one diameter is used throughout. Generally, however, this is not required, particularly if mud-flush is adopted, and casings which telescope into each other are used and this entails using a corresponding number of bits of decreasing diameter. In order that the final diameter shall be adequate this entails commencing with a hole of large diameter. To obviate this the hole may be reamed out whenever casing is required so that casing of one diameter only is used, fresh casing being added at the top and the casing string driven down to the required horizon.



(a) (b) (c)

FIG. 150. TYPES OF CASING

Casing may be flush-jointed, *a* (Fig. 150), where heavy driving is not necessary, swelled jointed, *b*, or screwed and socketed, *c*, where heavy driving may be necessary, or joined by welding. Each length

of casing is provided at the base with a shoe which may be toothed to assist driving, and at the top with a driving head (Fig. 151). The drilling string is fitted with clamps at the bottom and is then reciprocated as in "spudding," the clamp striking the driving head. For lifting the casing a heavy clamp (Fig. 152), is used which is fitted with serrated "slips," to grip flush-jointed casing.

Casing is sometimes cemented in position to strengthen it against

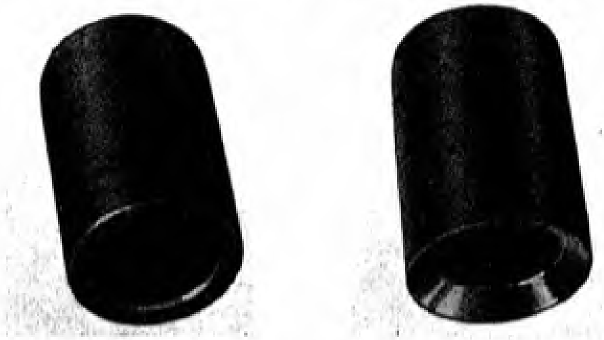


FIG. 151. DRIVE HEAD AND SHOE (CRAELIUS)

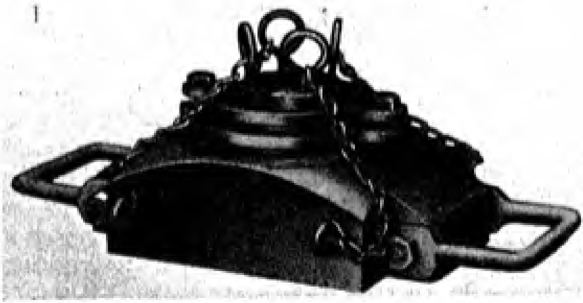


FIG. 152. CASING TUBE HOLDER (CRAELIUS)

attack by corrosive water and to assist in sealing off water, gas or oil. The cement is made thin and placed in the bottom of the hole. The hole and casing is filled with water and a tight cap is placed on the casing. This is then lowered and the cement is forced up between the casing and the sides of the hole.

When the purpose for which the hole was drilled is fulfilled the casing may be withdrawn. This may be accomplished by means of a screwed plug, or a Kind plug, consisting of an oak plug which is

enabled to grip the casing by dropping sharp grit between the plug and the casing. If the casing cannot be withdrawn in one length it may be cut into suitable lengths by means of pipe cutters. Screw or hydraulic jacks may also be used at the surface to draw casing.

ORGANIZATION OF DRILLING OPERATIONS

The choice of the method of drilling to be adopted depends on a great many factors including the depth to be reached, time available, capital and running cost of the equipment, water supply, type of strata to be drilled and facilities for transport. The limits of depths obtainable by the systems described have been indicated.

An important point is whether the drills are to be purchased and operated by the company on whose behalf drilling is to take place or whether the work should be let out to contractors, thus saving capital expenditure. Contract drilling is often faster but speed may be gained at the expense of core recovery so that a minimum percentage of core recovery is stipulated in contracts which may vary from 94 per cent in hard rock to 60 per cent in coal.

Continuous working over the twenty-four hours on three shifts gives a higher shift footage drilled than single or double shift working per day. Supervision, supplies, core recovery and cost of drilling are improved if three or four drilling rigs are supervised by one foreman who may also set bits in diamond drilling.

The drilling crew required depends upon the system of drilling adopted but is generally two—a charge driller and a helper. If a pair of drills are working within close proximity of each other a sampler is generally employed to take charge of the boring records received from the charge driller, take sludge (cuttings) samples and arrange for the sampling and filing of cores. Sludge samples, which are the sole evidence obtained in percussive boring, are recovered in wooden or galvanized settling tanks from the returning flushing water. A sample splitter, arranged with a number of parallel partitions leading from a common launder, enables a representative sample of convenient size to be obtained accurately and automatically from a bulk sludge sample.

After use all equipment must be cleaned out with meticulous care or unintentional "salting" of succeeding samples may occur. Where rotary drilling is adopted both the cores and the sludge are generally available. In working out assay values in metalliferous deposits due regard must be paid to the relative volumes of core and sludge samples and an effort must be made to recover the very finest sludge which may show relatively high values.

In metalliferous deposits the core is generally split by means of a

core splitter (Fig. 153), one half being assayed and the other kept for reference by filing in proper order of depth in boxes or cabinets. In boring for coal the whole of the core recovered is generally analysed after details of dirt bands, clarain, durain, etc., have been recorded, the bands being generally analysed separately.

In Great Britain, Sect. 23 of the Mining Industry Act, 1926, requires that all cores shall be kept for at least six months in order

FIG. 153. CORE SPLITTER (SULLIVAN)

that they may be inspected by an officer of the Department of Scientific and Industrial Research, while the Coal Industry Nationalization Act, 1946, Sect. 1 (2a) gives to the National Coal Board exclusively the right of searching and drilling for coal.

As many boreholes pass through water-bearing rocks or through upper waterlogged seams, it is essential for future safety that all boreholes when they have served their purpose should be effectively plugged. This is best assured by filling the hole with concrete using a cement which will set under water if necessary.

The proving of any area for economic minerals should be performed in a systematic manner or needless expense will be incurred in drilling. In boring for coal the holes are often sited at the corners of squares with relatively long sides of a mile or so. Where the material sought occurs in veins or masses the problem, in the first case, is to determine

the direction and useful mineral content and for this reason the holes are closer together on each side of the line which geological evidence suggests as the likely direction of the vein; in the second case the problem is to determine the vertical and lateral extent of the mass as well as its mineral content at different points. In this case holes on the corners of squares about 200 ft side are adopted.

The value of a borehole will be very much reduced if no adequate record is kept, and kept with meticulous accuracy, of all possible information of the strata penetrated, its hardness, whether water- or oil-bearing, economic minerals encountered (including coal seams) and any fossils found. With the record is generally incorporated a progress report of the borehole with reasons for delays or accidents

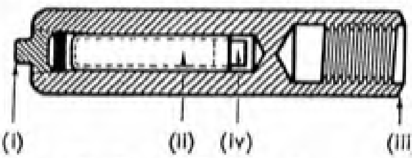


FIG. 154. TESTING TUBE OR CLINOMETER
(i) Brass plug; (ii) Glass vial; (iii) Rubber stopper; (iv) Brass body.

and the lengths and diameters of casing inserted. These records are diverse in make-up as they depend upon the purpose for which the hole is being drilled; but their proper and prompt entry is essential if the expensive drilling is to be justified and it is better to record too much than too little. It is as well to have the records checked at frequent intervals by a trained geologist so that proper descriptions of strata may be used and any fossils encountered properly identified.

Deviation of Boreholes

Boreholes drilled by percussive methods deviate less than those bored by rotary methods. In general, deviation increases to a marked degree with increase of depth and also depends upon the dip of the strata as deviation is generally along the line of full dip, particularly in steeply inclined strata. In rotary methods the longer the core-barrel used the less the deviation. In order that true depths and directions of boreholes may be determined it is necessary to measure both the amount of deviation and the direction in which it occurs. There are a number of instruments available, details of which are to be found in text-books of mine surveying.

The oldest method still used to a large extent is the hydrofluoric acid method (Fig. 154). In this a metal container carries a bottle of dilute hydrofluoric acid with rubber stoppers which is lowered into

the hole to a point at which a deviation reading is required. It is held there for a sufficient time to etch a line on the bottle. This is nearly the true horizontal line but needs correction for capillarity on the upper side of the bottle. The deviation from the vertical is measured by means of a goniometer, but it does not give the direction of deviation. In the Kiruna method copper is deposited electrolytically from solution leaving a rim similar to the line etched by hydrofluoric acid.

Other more accurate methods include the Gyroscopic-Clinograph method, electrically operated from batteries, which photographs time, temperature and inclination from the vertical on 16 mm film and can take one thousand readings descending then ascending the hole as a check. The Gyroscope maintains the casing on a fixed bearing. Photo-magnetic methods which photograph the image of a plumb-bob on a disc also recording direction of deviation, have also been used. The Briggs Clinophone transmits electrical signals communicating to the surface the position of a plumb-bob fitted with a needle relative to four electrodes arranged N, S, E and W, the needle and electrodes being immersed in an electrolyte. Signals are matched with a similar arrangement of needle and electrodes at the surface and the needle then reads the deviation and the direction of deviation.

Under-sea Drilling

Under-sea drilling, or off-shore boring, was developed by the oil companies for tapping under-sea oil reserves off the coast line of the Gulf of Mexico. This method is now extensively used in the Persian Gulf (Fig. 155).

In 1955, the National Coal Board constructed a sea boring tower for proving the extension of the Fife Coalfield under the Firth of Forth, particularly about two-and-a-half miles off the site of the new Seafield Colliery near Kirkcaldy. The drilling tower which stands 180 ft above sea level was built at a cost of £186,000, of specially fabricated tubular steel upon a heavy steel box-girder base, with hollow members which may be filled with air to provide buoyancy when the tower is being towed. The tower weighs approximately 500 tons. For towing, the base of the tower is "strapped" to two pontoons, each 170 ft long and 125 tons in weight. The drilling rods are shielded by a tubular casing 160 ft long and 24 in. diameter, down into the sea bed. The tower is intended for use in water up to 20 fathoms deep at low tide and is constructed so as to remain steady in all weathers. When lowered into position it rests securely on the sea bottom and is capable of withstanding an 80-mile-an-hour gale and waves up to 30 ft in height. The buildings, forming the living

quarters, baths, recreation room, galley, mess, power house and toilet facilities, are constructed to withstand wind pressures up to 50 lb/ft^2 and the walls have been specially constructed to provide

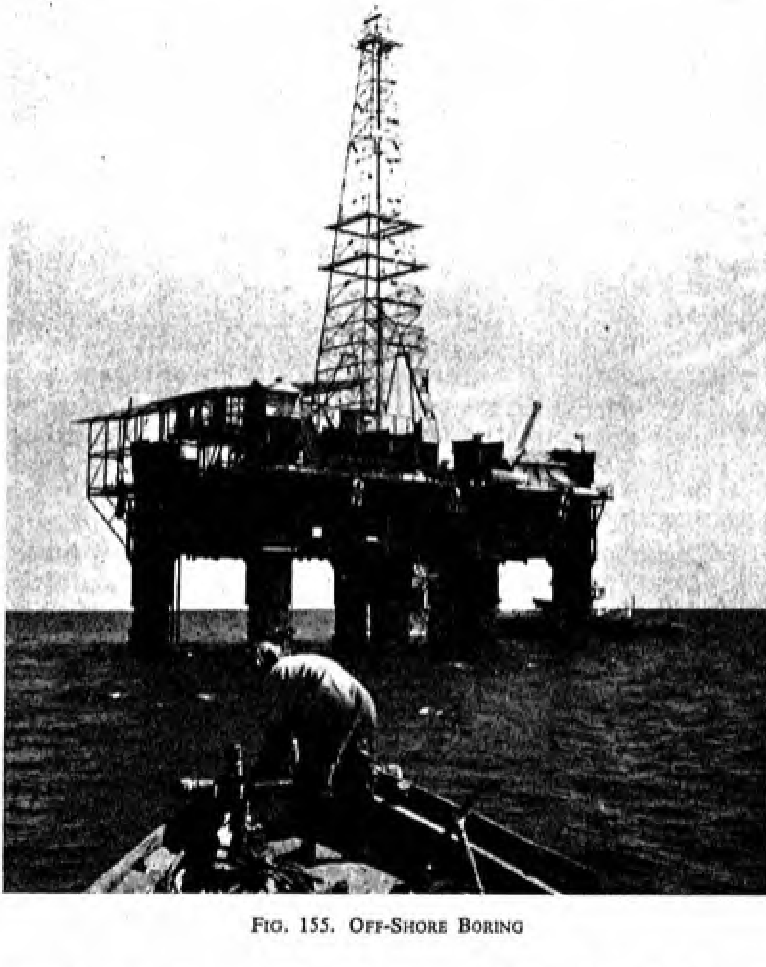


FIG. 155. OFF-SHORE BORING

warmth with a tower section of water-proof phenol-glued plywood, an inner skin fibre board and the cavity between packed with glass wool. Distillation plant is provided which can produce 42 gallons of fresh water an hour from sea water. The drilling equipment is capable of reaching a depth of at least 2,000 ft.

Underground Boring

Drilling operations may take place from underground workings either in a vertical direction or at any desired angle. If holes are to be drilled to a fairly great depth a hole is excavated above the site selected so that the drilling rods or pipes may be screwed and unscrewed in long lengths. The operation of drilling underground is

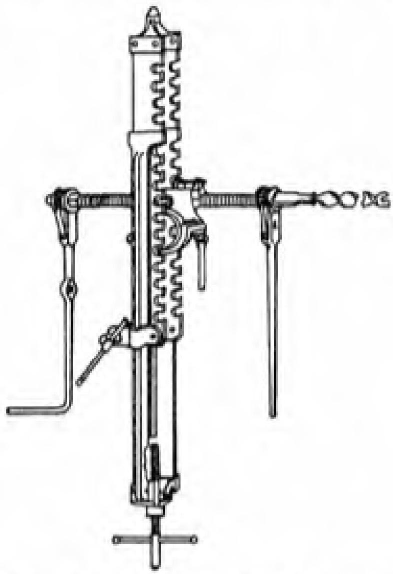


FIG. 156. HAND-BORING MACHINE WITH DIFFERENTIAL FEED

the same as on the surface except that, owing to limitations of space, the equipment is made as compact as possible.

Fig. 156 shows a hand boring machine of the rotary type which may be used to bore distances of 50–80 ft in any direction. The differential feed wheel shown allows the rate of feed to be reduced when boring hard rocks. Such a machine is useful for recovering a coal seam displaced by a small fault. Hammer drills may be adopted for capacities to 150 ft and even more. Sectionalized drill rods are used with screwed couplings and a water feed. Only sludge, of course, is recovered from the strata penetrated.

Figs. 157 and 158 illustrate diamond drills with capacities of 300 ft and 1,000 ft respectively for operation underground. The costs of underground drilling vary considerably with the system employed and the strata encountered. In underground prospecting for gold

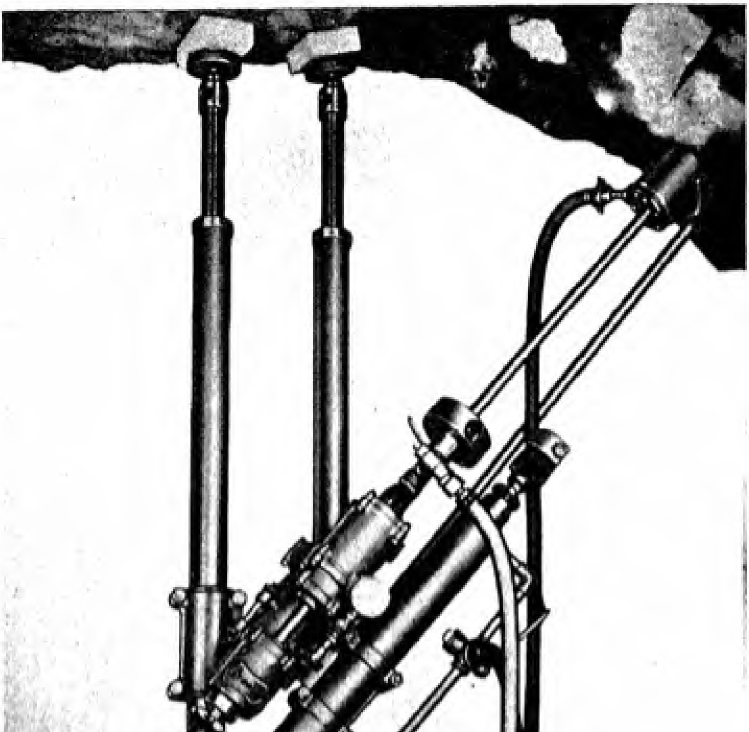


FIG. 157. X-2 DRILL WITH PNEUMATIC DRILL ROD EXTRACTOR

Mounted on double column for Underground Drilling: 300 ft Capacity
(Craelius)

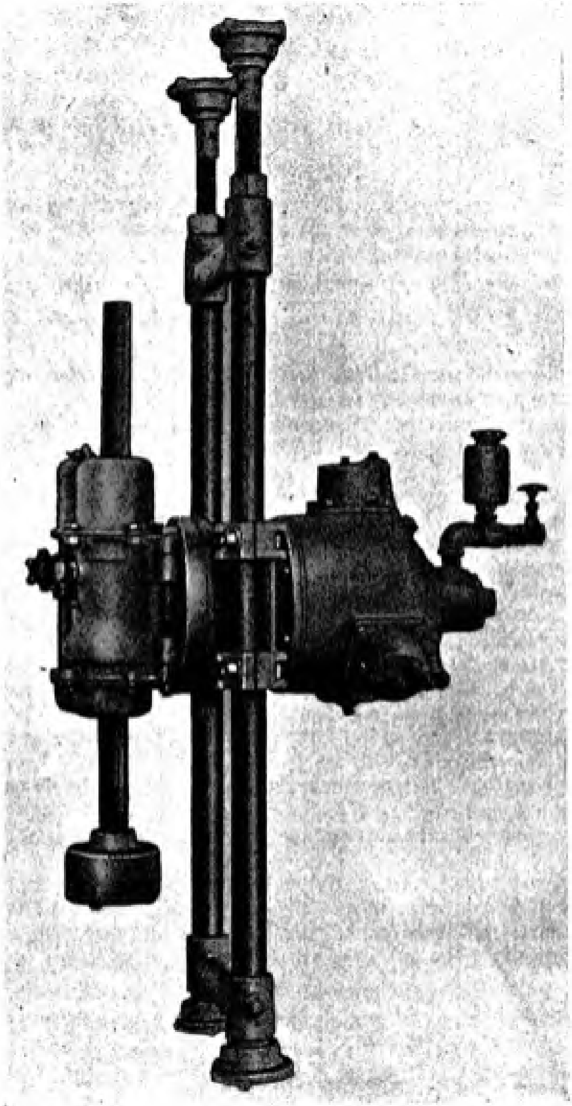


FIG. 158. SULLIVAN COLUMN-MOUNTED DIAMOND DRILL, 1,000 FT CAPACITY

using the diamond drill and holes up to 500 ft in length costs were 10s 2d and 9s 6d per ft in two cases covering a total footage of 10,700 ft, and 8s 6d and 9s per ft for shorter holes between 75 and 350 ft in length in limestone and granite, a tungsten carbide tipped bit $1\frac{5}{16}$ in. diam being used in the latter.

QUESTIONS

1. Describe the rotary system of boring in which cores are not obtained.

Discuss the usefulness or otherwise of this system of boring in proving the extension of concealed coalfields.

2. Compare the advantages and disadvantages of percussive and rotary systems of boring.

Describe the use of water and mud-flushing and the benefits to be derived from their use.

3. Give a general account of the mud-flush system of boring, indicating its application to coal prospecting.

Deal with the importance of mud-flush control and briefly describe any modification of the system which allows of uninterrupted recovery of rock samples.

4. Describe the diamond system of boring and the method of recovering cores of the strata penetrated.

Explain how a second core may be recovered from the same boring.

5. What methods are adopted to prevent the sides of boreholes collapsing during boring operations.

6. With the purpose of developing a new colliery an attempt is to be made to prove a concealed coalfield overlain by New Red Sandstone.

Outline the method you would adopt to obtain the greatest possible amount of useful information from a surface boring programme. State the nature of the information you would hope to obtain.

7. What methods may be adopted to determine the amount and direction of deviation of a borehole?

8. Under what circumstances may boreholes be required underground at collieries?

9. A new colliery is to be developed in an unworked extension of a producing coalfield.

The new area measures six miles by four miles and from existing data is expected to be traversed by two large faults.

Describe how you would explore the new area and determine its structure before embarking on the sinking of the shafts.

CHAPTER XIII

ACCESS TO MINERALS

THE common methods of providing access for the working of minerals are—

1. By practically-level cross-measure drifts or adit levels.
2. By inclined drifts or tunnels.
3. By inclined shafts similar to (2), but more highly inclined.
4. Vertical shafts circular, elliptical or rectangular.
5. Compound shafts, i.e. partly vertical and partly inclined.

In most cases two means of egress, generally intake and return airways, must by law be provided and combinations of two methods are common.

DRIFTS

Means of access by level and inclined drifts, (1) and (2) above are usually confined to shallower deposits but the reduction in the cost of drifting by mechanical means has increased the scope of these methods. This means of access has been preferred to vertical shafts with cage or skip winding in the reorganization of Lumphinnans Colliery in the Fife Coalfield, at Whitehill Colliery in the Lothians Coalfield and at Desford and Bestwood Collieries in the East Midlands Coalfield. Details of important drifts which have been driven for this purpose or in conjunction with vertical shafts for locomotive haulage, particularly where the horizon system of mining is adopted with practically level laterals and cross-cuts, are given on p. 250.

Inclined drifts have also been driven from the surface for exploiting small areas of coal with a life of 5–15 years at no great depth. Intensive methods of working are adopted and the output per man-shift is high and may attain 63 cwt. Direct rope haulage with drop-bottom mine cars of 2 tons capacity have been used with success in Scotland at Thornton and Benarty Collieries, and belt conveyors to the surface have been used at Bullcliffe Wood Colliery in West Yorkshire. In metalliferous mining inclined shafts are often driven in the deposits to be worked. They are less permanent than vertical shafts and winding and support are more difficult but they give an indication of the value of the deposit as they are being driven. Since valuable mineral is produced they are cheaper to drive than vertical

shafts although the methods of driving are similar. They are often used in mineral veins where the length of cross-cuts required to connect the veins to vertical shafts would be so great that the cost per ton of mineral to be worked becomes excessive.

Name of Colliery	Size of Drift	Inclination	Method of Drilling	Method of Debris Loading	Good Weekly Rate of Advance
Lumphinnans .	14 × 10 ft	1 in 3·8	Comp. Air frame	11 or 8 B.U. Joy to 26 in. conveyor belt	—
Whitehill .	12 × 8 ft	1 in 5	Hand held	14 B.U. Joy to main rope	—
Desford . .	11 × 9 ft	1 in 5	Hand held	hand to main rope	—
Knockshinnock	12 × 9 ft	1 in 120	Hand held	11 B.U. Joy to endless rope	40 yd
Nantgarw .	14 ft arch	Level	Hydro drill rig	60 Conway shovel to battery loco	38 yd
Llanharan .	14 ft arch	Level	Hand held	11 B.U. Joy to diesel loco	32 yd
Mardy . .	14 ft arch	Level	Hydro drill rig	Eimco 21 to diesel loco	32 yd
Cwm . .	12 ft arch	Level	Air leg	8 B.U. Joy	22 yd

The world record for the driving of such cross-cuts was achieved by the Doornfontein Gold Mining Co., in South Africa during the month of April, 1956, where the rate of point to point advance in a single road was 1,903 ft. The actual advance for 30 days was 2,170 ft and if account is taken of converted footage for traverse bays, etc., this becomes 2,238 ft. The best footage obtained in any 24 hours was 110 ft, and the four crews concerned are regularly breaking between 100 and 104 ft per day, which is greater than had been expected.

The twin cross-cuts, 10 ft × 10 ft and 9 ft × 9 ft finished, respectively, were being driven to a sub-vertical shaft a distance of some 9,000 ft for ventilation. Four six-hour shifts were worked per day and the equipment used included $2\frac{5}{8}$-in. diameter rock drills and $2\frac{1}{16}$-in. air legs, the drill steels used being 1 in. round hexagonal tungsten carbide tipped. Air operated mechanical loaders were

used and a 34-h.p. 5-ton diesel locomotive. A standard drilling platform was in use together with a manifold car, traversers and four ton side-discharge hoppers. The cross-cuts were laid with single track, 2-ft gauge of 45-lb rails. A 6-in. diameter compressed air column was used and a 4-in. water column; exhaust ventilation was through a 30-in. diameter pipe line with a 16-in. ventilation booster column. A 2-in. diameter water blast was in use for dust suppression.

Personnel employed included 21 Europeans and 30 Africans per shift. The excellent progress is ascribed to high morale of the crews, the four six-hour shifts per day, the use of suitable drilling and loading equipment and the high compressed air pressures maintained of 90 to 100 lb/in.^{2}, which gave high drilling and loading efficiencies.

In October, 1956, the Cementation Co., at Goldthorpe Colliery, Yorkshire, advanced the Bella Drift 63 yards in one week in a tunnel being driven from the surface through Coal Measure shales and sandstone at an inclination of 1 in 8·9. The drift, supported by steel arches, is 12 ft 9 in. × 16 ft wide with the arches 2 ft 6½ in. centres. Five Atlas Copco wet type drilling machines were used and loading was carried out by an Eimco 40H loader.

Drifting in the United Kingdom during recent years has been mainly for projects of the National Coal Board and the North of Scotland Hydro Electric Board. The conditions under which drifting was carried out for the two organizations are very different. Tunnels for hydro-electric projects have normally been through strata which required little or no supporting and the regulations governing shot-firing procedures and general operations were much less vigorous than those applying to National Coal Board tunnels.

In the hydro-electric tunnels rates of advance in tunnels of the order of 10 ft in diameter are commonly in excess of 300 ft per week, the record performance of 557 ft in seven days being achieved in 1956 by the Mitchell Construction Co., at the St. Fillans project.

The most commonly used equipment in the hydro-electric tunnels are Eimco 21 rocker shovel loaders and airleg-mounted drills. This equipment was used in the St. Fillans tunnel. In N.C.B. tunnels the Eimco 21 rocker shovel loaders with airleg-mounted drills are also the equipment most commonly used. Other common loading equipments are the Eimco 40, the Mavor and Coulson M.C.3, and M.C.2 gathering arm type loaders, the Sullivan Slusher (for inclined drifts) and the Conway 60. Drilling equipment in use other than airleg-mounted drills comprise drill rigs or "jumbos" carrying two or three heavy percussive drifters. Limited use is made of the Hardypick rotary drilling machine and the German rotary-percussive

drills are being introduced mainly on an experimental basis at present.

The limitations imposed on N.C.B. tunnels by the regulations applying to coal mining have been mentioned above. In addition the rate of advance in many cases is limited by the haulage, winding and dirt disposal capacity of the colliery. The majority of N.C.B. tunnels are being driven at collieries which are in full production and the transport of stone, materials and men to and from the tunnel is in addition to the normal demand on the colliery services for coal production. Due mainly to these various limitations the performances in N.C.B. tunnels do not compare favourably with those attained in the hydro-electric and foreign tunnels mentioned above. A number of very good performances have, however, been achieved. The performance at Goldthorpe has already been mentioned. More recently a new drivage at Cynheidre has been advanced 183 yards in one month. At Bank Hall Colliery in Lancashire a drivage of 1,400 yards total length was driven at an average rate of 96 ft per week from start to finish. In N.C.B. projects, where careful planning and phasing of a whole project (of which drifting is only a part) is required, the rate of drivage sustained over a long period is of course more important than the attainment of high rates in a few isolated periods. Drivages at Manvers Main colliery in Yorkshire have averaged 25–30 yards per week over long periods. At this colliery an interesting combination of equipment has been developed. Two Eimco 21 rocker shovel loaders have been adapted for side loading on to a shuttle conveyor, and a drill rig carrying three heavy drills is mounted on the conveyor facilitating and speeding movement of the rig to and from the face.

Investigations carried out in 1955 and 1956 showed the practicability of faster rates of drivage in N.C.B. tunnels even with present equipment. Where the limitations of haulage, winding and dirt disposal capacity can be overcome, the investigations showed rates of advance of the order of 50 yards per week to be a reasonable attainment.

One subsequent step towards the raising of the general level of tunnelling performance has been the setting up of a National Demonstration Tunnel at Ashton Moss in Lancashire. The average weekly advance in this tunnel for the last 6 months of 1957 has been 40–45 yards per week.

THE SINKING OF VERTICAL SHAFTS

In a majority of cases in which coal seams are to be worked at a depth greater than 250 yd vertical shafts will be adopted to gain

access to the seams. The thickness of the coal seams expressed as a percentage of the Coal Measures in which they occur will largely determine whether the pit-bottom and main roads will be established in particular seams or whether connection to the seams will be by means of level cross-cuts and laterals in the horizon system of mining. If the percentage is greater than $2\frac{1}{2}$ the latter system is worth examination from the economies it offers in main road maintenance and the saving which results from the use of locomotive haulage on these practically level main roads.

The exact position of the shafts in the area to be exploited will depend upon a number of factors the relative importance of which will tend to vary in each case and will therefore require to be "weighted" in accordance with experience. These are—

1. Sufficiently level or approximately level ground for the construction of colliery railway sidings. A contoured map of the royalty will assist in the search for ample facilities for present requirements and future extensions. In mountainous areas with steep-sided valleys, as often occur in South Wales, great difficulty and undue cramping of surface layout may be unavoidable.

2. The position and depth of the seams to be worked and the method or methods of working proposed.

3. The sterilization of thin or poor quality coal in shaft pillars. In folded strata the seams may be notably thinner on the crests of anticlines and this fact may be utilized in reducing the tonnage of coal sterilized if shaft pillars are sited in these positions.

4. Proximity to one, or preferably more than one, railway line although the advantage of competition has largely disappeared with the nationalization of railways in this country.

5. Storage capacity of sidings to be provided should if possible amount to three days' output of loaded wagons and two days' output of empty wagons although less capacity than this has proved sufficient near towns with regular clearance of sidings by railway companies' locomotives.

6. Road and canal transport facilities.

7. Disposal of dirt from pits and screening plant.

8. Water supply for boilers, condensers, washeries and coke ovens.

9. Power supply particularly if self-generated power is not to be provided. Two feeders at least should serve the colliery if this has no power plant of its own. The tendency is towards purchased power either from the National Grid or a Group Power station serving the area.

10. Availability of personnel for working the colliery.

11. Drainage facilities to dispose of effluent and mine water.

12. Ventilation requirements including the benefits of ascensional ventilation in inclined seams. In large royalties peripheral upcast shafts may be required to limit the length and resistance of trunk airways. Such a colliery, generally with a high annual output, is known as a "combined mine."

13. Provision of reserve areas for future plant extensions, or coke oven plant replacement, brickworks, power station and coal stocking ground for storage and for continuity of supply in emergency to coke ovens and power station. Since the life of coke ovens is limited to about 20 years a replacement battery must be erected towards the end of the life of the existing battery.

14. Geological considerations including the avoidance of water-logged strata expensive to penetrate and alluvial and water-bearing ground where foundations for plant would be expensive. The vicinity of large faults also should be avoided.

The size of the shaft to be sunk will depend upon whether the output is to be wound in cages or skips, the output and the ventilation required, the size of mine car or tub to be used and the type of cage guide to be installed.

On the Continent where great thicknesses of Mesozoic rocks have to be penetrated by freezing methods and where tubbing is used for permanent watertight linings, shafts rarely exceed 20 ft in diameter. In this country the National Coal Board has drawn up specifications for the standardization of shaft, roadway and mine-car dimensions as follows.

Standard Shaft Sizes for New Mines and Major Reconstruction Schemes

After considering current British and Continental practice and requirements in this country, it has been recommended that certain shaft sizes should be accepted as standard for new mines and major reconstruction schemes. With double-winding, i.e. four cages in one shaft, the shaft diameters should be standardized at 24 ft and 20 ft, and only in exceptional circumstances should 22 ft and 26 ft diam shafts be necessary. The use of this size of shaft will be determined largely by ventilation requirements particularly where extensive undersea coalfields have to be developed. For single-winding (two cages in one shaft) the shaft diameters should be standardized at 20 ft, 18 ft and 16 ft. There are many obvious advantages to be obtained from standardization of shaft sizes, not least being the readiness with which a standard range of mine cars can be adopted.

Mine Cars

Initially, it was considered that the first step towards standardization should be in respect of capacities and dimensions, and it was agreed that the upper limit of capacity should be 3 tons and the lower limit 1½ tons. The opinion is held that such a range will meet the output requirements of most pits, and that only in special circumstances will a larger mine car be necessary. Certain

standards will, however, be agreed at a later date for mine cars with capacities from 3–6 tons.

Table I gives the principal dimensions of a standard range of eleven mine cars which have been recommended for consideration, though yet subject to confirmation. Three cars are recommended for new pits, Car *E* for new sinkings having four cages in 20 ft-diam shafts, Car *H* for new sinkings having two cages in 16 ft-diam shafts, and Car *J* for new sinkings having four cages in 24 ft-diam shafts or two cages in 20 ft- and 18 ft-diam shafts respectively. Any of these cars, where suitable, could, of course, be used in a reconstruction scheme. Due to the wide differences in shaft sizes, it may be necessary to consider some standard variation of the proposed range of mine cars. This might be accomplished by varying the lengths and heights by increments of 6 in. and 3 in. respectively. To assist manufacturers and also achieve uniformity in design a general specification has been prepared.

Table I

Suggested Range of Standard Mine Cars for New Mines and Reconstructions

Car Ref. No.	Cap. in ft^3	Nominal Pay Load	Recc. Rail Gauge	Width of Body	Depth of Body	Length of Body	Total Height above Rail	Length over Buffers	Wheel-base
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
		Tons	ft in.	ft in.	ft in.	ft in.	ft in.	ft in.	ft in.
A	67		2 0	3 0	3 2	7 3	4 6	8 0	3 0
B	62	1½	2 0	3 3	3 2	6 3	4 6	7 0	2 6
C	61		2 6	3 9	3 2	5 3	4 6	6 0	2 3
D	85		2 0	3 0	3 2	9 3	4 6	10 0	4 0
E	82	2	2 0	3 3	3 2	8 3	4 6	9 0	3 6
F	83		2 6	3 9	3 2	7 3	4 6	8 0	3 0
G	110		2 0	3 6	3 2	10 3	4 6	11 0	4 6
H	106	2½	2 6	3 9	3 2	9 3	4 6	10 0	4 0
I	101		3 0	4 0	3 2	8 3	4 6	9 0	3 6
J	129	3	2 6	3 9	3 2	11 3	4 6	12 0	5 0
K	126		3 0	4 0	3 2	10 3	4 6	11 0	4 6
L	142	3½	3 0	4 0	3 2	11 3	4 6	12 0	5 0
M (DB)	85	2	3 6	4 4	2 0	10 3	3 0	11 0	—

Car E—Recommended standard mine car for new sinkings having four cages in 20 ft-diam shafts.

Car H—Recommended standard mine car for new sinkings having two cages in 16 ft-diam shafts.

Car J—Recommended standard mine car for new sinkings having four cages in a 24 ft-diam shaft and new sinkings having two cages in 20 ft- and 18 ft-diam shafts.

Car M—2 tons drop bottom for use in shallow Drift Mines.

In selecting a suitable mine car from the range, regard should first be had to shaft capacity. If the car selected cannot be accommodated in the shaft, the

next lower car in the range should be chosen, and so on. When a car has been chosen which is suitable to the shaft, but which is then found not to give the desired winding capacity, consideration should be given to alteration in the shaft layout. For example, it should be observed that in a given size of shaft, a larger cage can be utilized with rigid guides than with flexible guides. Table II shows the suggested standard range of mine cars in relation to minimum shaft diameters and minimum roadway cross-section. The importance of large-capacity cars in any transport reconstruction cannot be too strongly emphasized. Wide variations in existing transport systems and mining conditions make the problem of standardization very complex. Nevertheless, every effort should be made by technical managements to plan reorganization schemes on the basis of the standards.

Table II

Proposed Standard Cars (Table I) in Relation to Minimum Shaft Diameters and Minimum Roadway Cross-section. Single Winding

Car Ref. (Table I)	Car Capacity	Rigid Guides with Minimum Clearance	Rigid Guides with Normal Clearance	Flexible Guides with Normal Clearance	Minimum Size of Roadway Required for Double Traffic
(1)	(2)	(3)	(4)	(5)	(6)
	Tons	ft	ft	ft	ft
A	1¼	12	13	14	12 × 8
B	1⅓	12	13	14	12 × 8
C	1½	12	13	14	12 × 8
D	2	14	15	16	12 × 8
E	2	13	14	15	13 × 9
F	2	13	14	15	13 × 9
G	2¼	15	16	17	13 × 9
H	2⅓	15	15	17	13 × 9
I	2½	14	15	16	13 × 9
J	3	16	17	18	13 × 9
K	3	16	16	18	13 × 9

Note—Shaft diameters taken to the nearest foot.

The following minimum standard shaft clearances have been adopted—

In column 3—

Minimum clearance between cages . . . . . . 6 in.
Minimum clearance between cage corner and shaft wall . 6 in.
Cage corners chamfered to further economize space.

In column 4—

Minimum clearance between cages . . . . . . 6 in.
Minimum clearance between cage corner and shaft wall . 8 in.
Normal square corners on cages.

In column 5—

Minimum clearance between cages . . . . . . 18 in.
Minimum clearance between cage and shaft wall . . 12 in.
Normal square corners on cages.

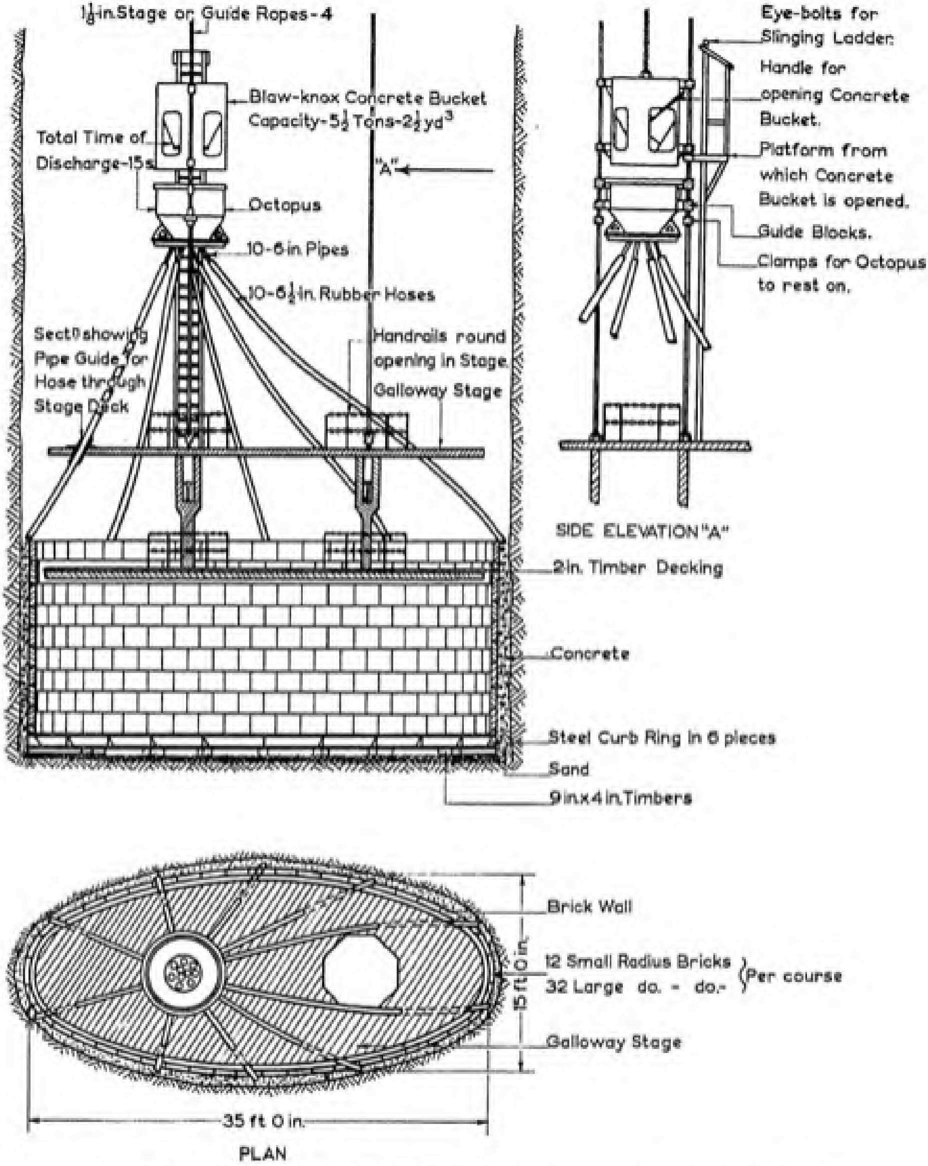


FIG. 159. ELLIPTICAL SHAFT WITH BLAW-KNOX CONCRETING "OCTOPUS" (Blunt)

Rectangular and Elliptical Shafts

Formerly rectangular shafts were commonly used in coal-mining particularly in Scotland and they are still commonly adopted in metal mines throughout the world both for vertical and inclined shafts. However, circular and elliptical shafts (Fig. 159), resist lateral pressure better and for deep shafts these shapes are generally preferred. Rectangular shafts were generally lined with wooden "barring" as they were sunk and thus no temporary lining was

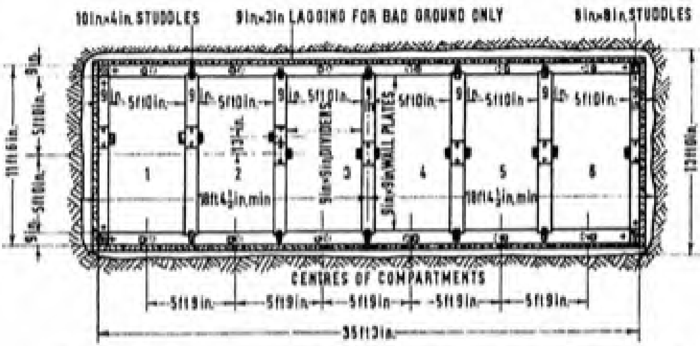


FIG. 160. TIMBERING OF A RECTANGULAR SHAFT (AIRTH & DOLAN)

needed but a concrete fireproof lining is now generally adopted. They are usually divided into a number of square or rectangular compartments for hoisting, ladderways, ventilation, etc., separated by buntons or dividers as shown in Fig. 160.

Elliptical shafts are a compromise between rectangular and circular shafts and are also divided into compartments like rectangular shafts. Modern elliptical shafts are generally lined with concrete.

Circular Shafts

Unless the ground to be sunk through is well known geologically it is advisable to put down a borehole and recover cores of the ground to be penetrated, particularly if the presence of heavily water-bearing strata is suspected. The borehole should be adjacent to, but not in the area of the site of, the shaft, unless it is intended to employ the freezing method of sinking through water-bearing strata. In reviewing the methods of sinking employed in different circumstances the first example will be a dry sinking in normal ground without geological complications.

Collective expert opinion favours postponing the erection of the main headgear over the shaft until this has been sunk to the stone head and lined to the surface with brick or concrete. If the headgear is built before sinking is commenced there is danger that, if soft ground is encountered or excessive rainfall occurs, the foundations of one or more of the headgear legs may be disturbed during sinking and trouble may continue throughout the life of the colliery. If the depth of the stone head is not excessive, say 20 ft, the debris from the sinking is thrown out onto stages and so to the surface by shovels. If deeper than 20 ft it is usual to employ a power-driven crane, such as a locomotive crane. This has a jib approximately 30 ft in length so that the weight of the crane, which will be about 5 tons, is concentrated at a point at least 10 ft away from the side of the shaft. Hoppits are used in conjunction with a crane to a depth of 100 ft. These are tipped into Jubilee trucks, railway wagons, dumpers or belt conveyors according to the method of transporting the dirt to the disposal area chosen. In this preliminary stage, in order to avoid shattering the ground, excavation is carried out as far as possible without the use of explosives, pneumatic picks being commonly used.

Simultaneously with these operations, temporary offices, stores, workshops with smiths' fires and carpenters' shops, power supply, water supply and changing and living accommodation for sinkers must be provided. An explosives store should be erected provided with hot-water to prevent freezing of the explosives in very cold weather.

Shaft Centre

In order to fix the foundations of the winding engines and headgear it is necessary to determine the centre of the shaft. This is an important reference point for the whole of the colliery surface plant and is of course also used to fix the lining of the shaft and to maintain its verticality, a tolerance of about 3 in. being provided by sinking the shaft oversize by that amount. To fix the centre four blocks of concrete about 6 in. square in cross-section are sunk into the ground for a depth of 6 ft at a distance of 30 ft from the edge of the shaft their position being fixed by a very accurate survey carried out by means of a theodolite. The blocks are arranged in pairs at right angles, one pair in line with the centre line of the shaft and the winding engine and the other pair at right angles to the first pair so that the intersection of the lines marks the exact centre of the shaft, the lines being marked on metal plates let into the concrete. These lines are extended later to fix the position of surface plant.

At first, until the permanent centre-line apparatus is installed (as soon as the first length of sinking and shaft walling is completed), a light section girder is placed across the shaft with a piano wire passing through a hole in the beam, which is moved until the wire is centred; then supports are arranged so that the beam may be placed in the same position subsequently. The excavation required at the surface for the shaft and the thickness of lining inserted at the shaft collar, which is generally 2 ft 3 in. or 3 ft, is marked by a ring of pegs.

A radius rod is used subsequently, in conjunction with the plumb line to mark the shaft centre, to fix the position of the inside and outside diameters of the lining and to correctly position bricking curbs. This consists of a wooden rod $1\frac{1}{2}$ in. square at the outer end and 2 in. square at the inner end, the outer end being tapered and protected by a metal cap. At the thicker end saw cuts are made at distances from the point of the metal cap at the other end corresponding to the inside diameter of the shaft and the outside diameters for different thicknesses of linings. By means of a radius rod placed at the correct saw cut for the required thickness of lining the outside diameter of the excavation required can be swept out and marked.

Temporary Support

As the excavation proceeds downwards from the surface it needs to be temporarily supported and for this purpose skeleton rings connected by hangers and backing boards are employed. The steel skeleton rings are from 4 in. to $4\frac{1}{2}$ in. deep and $\frac{7}{8}$ in. to $1\frac{1}{4}$ in. thick, 4 in. × 1 in. being a common size. The rings are in segments 6 to 8 ft in length, the number of segments required depending on the diameter of the excavation. Each segment has three or four holes in each end spaced at 4 in. centres and the segments are connected by fishplates of the same section with 6 or 8 holes into which are fitted 1 in. square-necked bolts $3\frac{1}{2}$ in. in length. Normally the segments are butt-jointed but, where a thicker lining is required and the excavation is wider, only the two end holes in the fishplates are used leaving a gap of 8 in. between the segments. For matching-in a long fishplate is provided 6 ft in length with a row of holes. Accommodation can also be obtained by overlapping instead of butt-jointing the segments so that considerable latitude is available in increasing or decreasing the perimeter of the skeleton rings.

The uppermost skeleton ring, i.e. the first inserted, is suspended from rails driven into the ground on a ring 10 yd from the shaft side in a direction sloping towards the centre of the shaft. Each segment

is connected by a chain or wire rope led over a sleeper at the edge of the shaft to a separate anchoring rail, the tension of the chains or ropes being equalized to distribute the load over a considerable area. The next ring below is suspended from that above by hangers

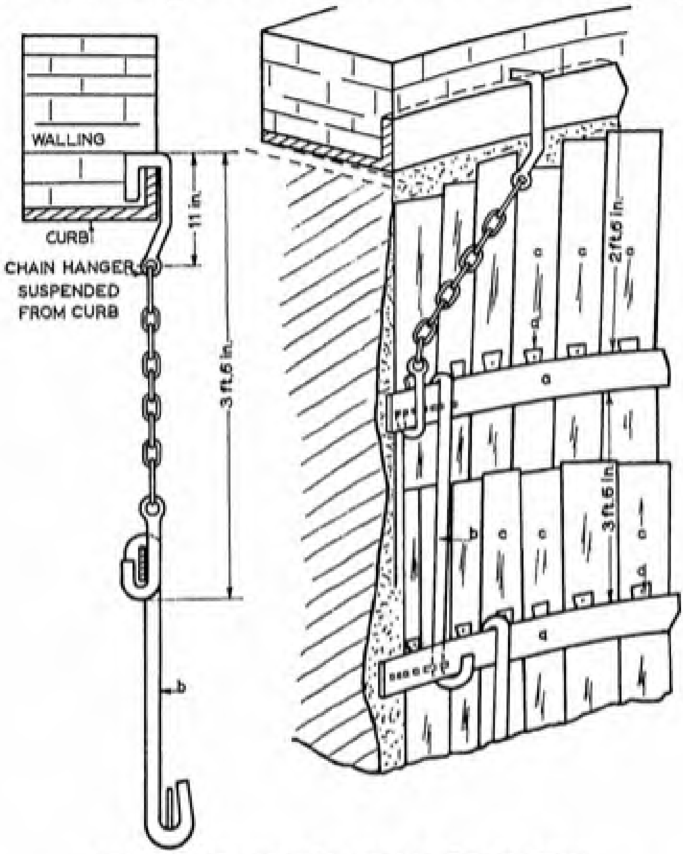


FIG. 161. TEMPORARY SUPPORT IN A SINKING SHAFT
Showing also the method of supporting the First Ring (*a*) Skeleton rings: (*b*) Hangers; (*c*) Backing boards; (*d*) Wedges.

of wrought iron, *b* (Fig. 161), 1 in. diam or 1 in. square in cross-section bent at the ends in opposite directions to fit loosely on the rings above and below. The normal length of these hangers is 4 ft 6 in. but in heavy ground the rings are required to be nearer together so that sets of hangers 3 ft, 2 ft 6 in. and 2 ft in length are also provided. The third ring down is given separate anchors and chains on the surface.

Behind the rings are placed backing boards 6 in. wide, 1 in. to $1\frac{1}{8}$ in. thick and 4 ft 6 in. in length either skin-to-skin or, in heavier ground, overlapped 3 in. held in place by wedges 3 in. $\times$ 3 in. and tapering to a point in their length of 9 in., placed in the middle of the board between it and the skeleton ring. Any irregularity in the periphery is supported by pieces of timber behind the backing boards. By these means the shaft is excavated to the stonehead and temporarily supported. Subsequent operations depend upon whether the permanent lining of the shaft is to be of brickwork, concrete or reinforced concrete.

Experiments are proceeding with chain mesh as a temporary lining carried by roof bolts let into the shaft periphery. The mesh is afterwards incorporated as reinforcement in a concrete shaft lining.

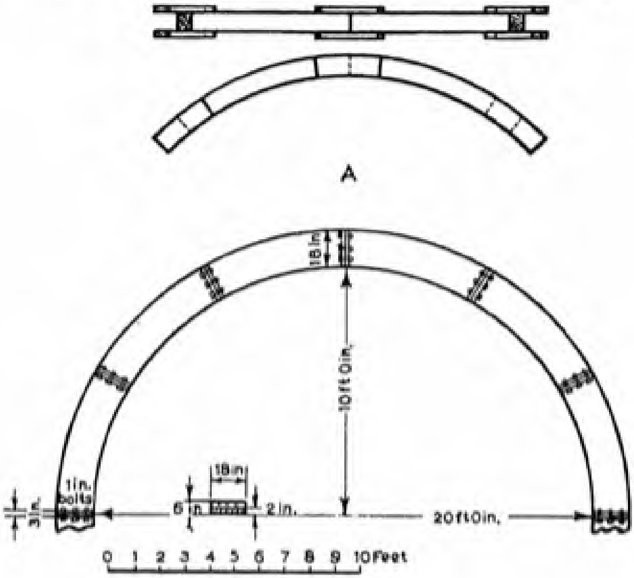
Permanent Brickwork Lining

The foundation for the first length of a brickwork lining is a curb or crib of oak, cast iron or concrete set upon a suitable bed prepared and cut back in the stonehead. If a wooden curb is used it will be either 4 in. or 8 in. deep and about 14 in. wide. The deeper curb would be constructed of two layers of oak placed one upon the other with the joint broken, i.e. half-lap, each layer consisting of a number of segments depending on the size of the shaft, there being some 16 in each layer for a 21 ft finished-diameter shaft. The layers are connected by $\frac{3}{4}$ in. bolts, $7\frac{1}{2}$ in. long, countersunk into both layers (Fig. 162*A*).

Before it is sent down the pit the curb should be erected on a curb-table constructed on a level piece of ground, somewhat greater in diameter than the shaft in which a level bed of concrete about 4 in. thick is laid down with a centre pivot to take a wooden radius rod. The curb on the table is bolted up and tested for a truly circular periphery and any inaccuracy is corrected. The segments of the curb are sent down the shaft and erected. A light girder is placed across the shaft and the plumb line is lowered. By means of the radius rod the inner edge of the curb is centred by driving wedges behind the curb between it and the side of the excavation. The curb is next levelled by means of a straight-edge and level, thin wedges underneath the curb being used for this purpose. The centring is again checked and when both centring and levelling are correct the back wedges behind the curb are tightened up and concrete is run between the excavation and the top of the curb.

Wooden curbs are strong and elastic but they are expensive to manufacture and may perish in time. It takes approximately half-a-shift to lay and level a wooden curb and centre it upon a prepared

bed. The time to erect and check in a similar manner an iron curb, also in segments (Fig. 162*b*), is about quarter of a shift. Iron curbs are, however, more brittle than wooden or concrete curbs and care has to be taken when blasting during subsequent sinking operations



B

FIG. 162. BRICKING CURBS
A. Wood. *B*. Cast iron.

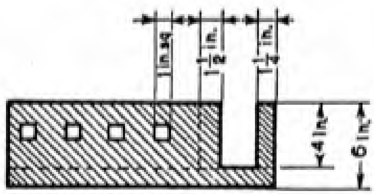


FIG. 163. SECTION OF CAST-IRON WATER GARLAND

below them. They are often combined with a water-garland as shown in Fig. 163.

Owing to the reduced amount of preparation work required concrete curbs, which are strong and not easily damaged by blasting, are becoming increasingly popular. The ground is cut back in the form of a wedge as shown in Fig. 164. In order to key into the brick-work below, boards levelled on a foundation of loose broken bricks,

wood blocks and ashes are used and concentric with the inside periphery of the shaft two rings of sheet steel shuttering are erected behind which concrete is well rammed. When this has set the shuttering, boards and loose packing are removed. If the shaft is wet arrangements must be made to conduct the water from the sides of the shaft clear of the concrete curb while it is setting.

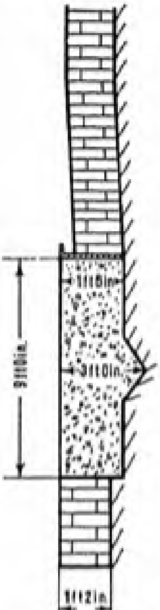


FIG. 164. CONCRETE CURB WITH CAST-IRON WATER GARLAND

The standard thicknesses of brickwork linings of shafts are 9, 14, 18, 24 and 27 in. but the three latter thicknesses are used only in the vicinity of the shaft collar or in portions of the shaft with sides of exceptional weakness. Generally unless the shaft is of abnormally large diameter, greater than 22 ft, 14 in. brickwork is normally adequate and 9 in. brickwork often adopted. Unless the shaft is less than 15 ft in diameter special shaped bricks are not required but ordinary hard well-burned bricks with a low porosity and good metallic ring of standard dimensions, approximately $8\frac{3}{4}$ in. $\times$ $4\frac{1}{4}$ in. $\times$ $2\frac{3}{4}$ in., are used. The courses of brickwork should be suitably bonded for strength, the bonds commonly adopted being alternate stretcher and header courses and one header and three stretcher courses, the latter being somewhat easier to lay. In wet ground cement mortar should be used.

In order to distribute the pressure evenly over the lining in a dry sinking, well-burnt ashes are packed between the back of the brickwork and the shaft side. If rigid guides are used concrete may be adopted to grip the buntons carrying the guides firmly. If the shaft is wet ashes would have a tendency to pack so broken rubble or solid concrete is preferred.

If an oak or a cast-iron curb has been used the brickwork is racked back about $2\frac{1}{4}$ in. ($\frac{1}{4}$ brick) per course until the thickness of lining required at the top of the shaft is obtained. If a concrete curb is adopted it will extend for some distance up the shaft and the brickwork above it will be of the required thickness to the surface. Whatever type of curb is used plumb lines down the finished circumference of the shaft are dropped from the surface to ensure the lining is vertical.

Means must also be provided for suspending and raising the walling scaffold in the shaft. In the example shown in Fig. 165 used at the Brookhouse sinking 18 ft diam sunk in 1929, the main members consist of 12 in. $\times$ 9 in. pitch pine timbers. The main doors in the

centre are of oak 3 in. in thickness with $\frac{3}{4}$ in. bolts. The remainder of the decking is of 3 in. deal. Alternatively the main members of the scaffold may be of steel sections. That at Babbington No. 4 shaft, 18 ft 2 in. finished diameter, was 17 ft 2 in. diam and was built up of four channels 10 in. $\times$ $3\frac{1}{2}$ in. and 4 in. $\times$ 4 in. $\times$ $\frac{5}{8}$ in. angles leaving a central aperature 7 ft^2. On this main framework of channels and angles were fastened 9 in. $\times$ 4 in. timbers strengthened by flat steel

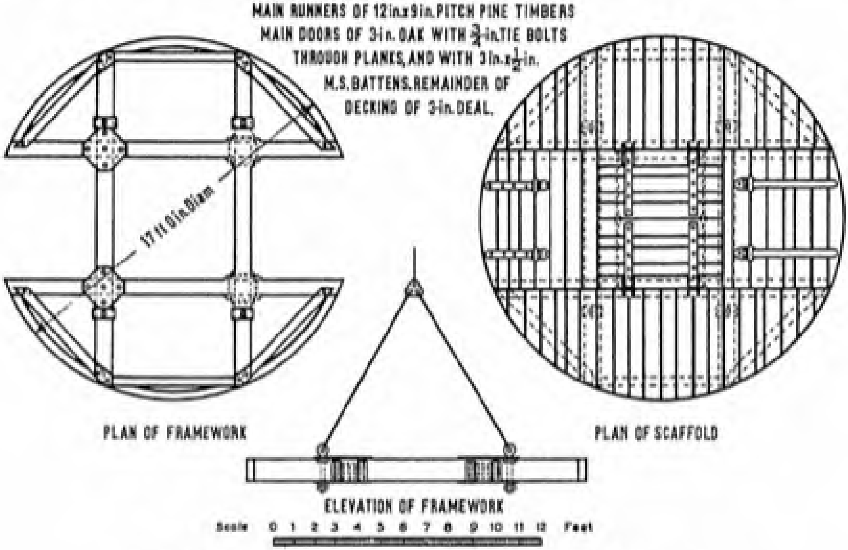


FIG. 165. SINKING SCAFFOLD USED AT BROOKHOUSE SINKING

straps 3 in. $\times$ $\frac{5}{8}$ in. with $\frac{3}{4}$ in. bolts. On opposite sides of the scaffold were hinged doors 7 ft $\times$ 3 ft which could be raised to pass ventilation pipes and other obstructions at the side of the shaft and two smaller doors to pass buntons fixed at the shaft sides. When men were working on the scaffold the central opening was closed by two doors. When these were opened a rail attached to the "bull" chains suspending the scaffold was placed round the opening. Four heavy sliding bolts were provided to hold the scaffold during walling but these are often not used except when re-capping the scaffold ropes. Four heavy wedges attached to the scaffold by chains were used to drop between the wall and the scaffold to prevent it from swinging when hanging freely.

As it is assumed that the permanent headgear is ultimately to be used for sinking but has not yet been erected it is necessary to provide

means of suspending the walling scaffold temporarily. These may comprise long girders across the shaft with the ends supported on cross baulks in order to distribute the weight. The girders are connected to the scaffold by chain blocks by which it may be raised or lowered. These are used in conjunction with ropes capped at both ends, 10 and 20 ft in length, which, since the blocks give a lift of 10 ft, enables 40 ft of walling to be carried out. Alternatively a framework of 6 in. × 5 in. girders may be erected at the top of the shaft. Instead of ropes, chains may be adopted with a D link on to each chain as a safety precaution should the blocks fail.

Bricking of the lining is carried out to the surface by these means and the temporary supporting rings and deals removed, pockets being left in the brickwork in which the compound girders to carry the kep-gear will be fixed. An excavation is left parallel with the rope line between the winding engine and the headgear pulleys in which the permanent centre-line apparatus is erected. This consists (Fig. 166), of a channel 6 in. × 3 in. with two stops bolted to the channel and two corresponding stops grouted into the floor of the duct so placed that a small hole near the end of the channel is exactly in the centre of the shaft when the stops are in contact. Sounding cable may be used as the centre line and has the advantage of being non-corrosive, non-spinning and non-stretching. On the opposite side of the shaft to the centre-line apparatus is a conduit leading to a surface drain down which water from the sinking may be discharged.

In addition to ordinary standard bricks, concrete and brick blocks three or four times the weight of a standard brick may be used for lining. The number of joints and the work of building is somewhat reduced.

Concrete Lining

Where a concrete lining is to be adopted the initial operation, when excavation has reached the stonehead, is the construction of a concrete curb some 2 ft 6 in. wide and tapering to the normal thickness of the lining in a height of 4 ft.

The concrete is retained until set by shuttering consisting of segments about 5 ft in length, 2 ft 6 in. deep and ¼ in. thick, the length being such that a suitable number of equal segments gives the correct finished shaft diameter. Each segment has riveted round its edges 2½ in. × 2½ in. or 3 in. × 3 in. angle iron. On the bottom and on one side the angle iron overlaps the plate by ¼ in., but on the top and the other side the plate overlaps the angle iron by the same amount. It will be seen that this arrangement forms a male and female joint and a baffle which prevents leakage of cement.

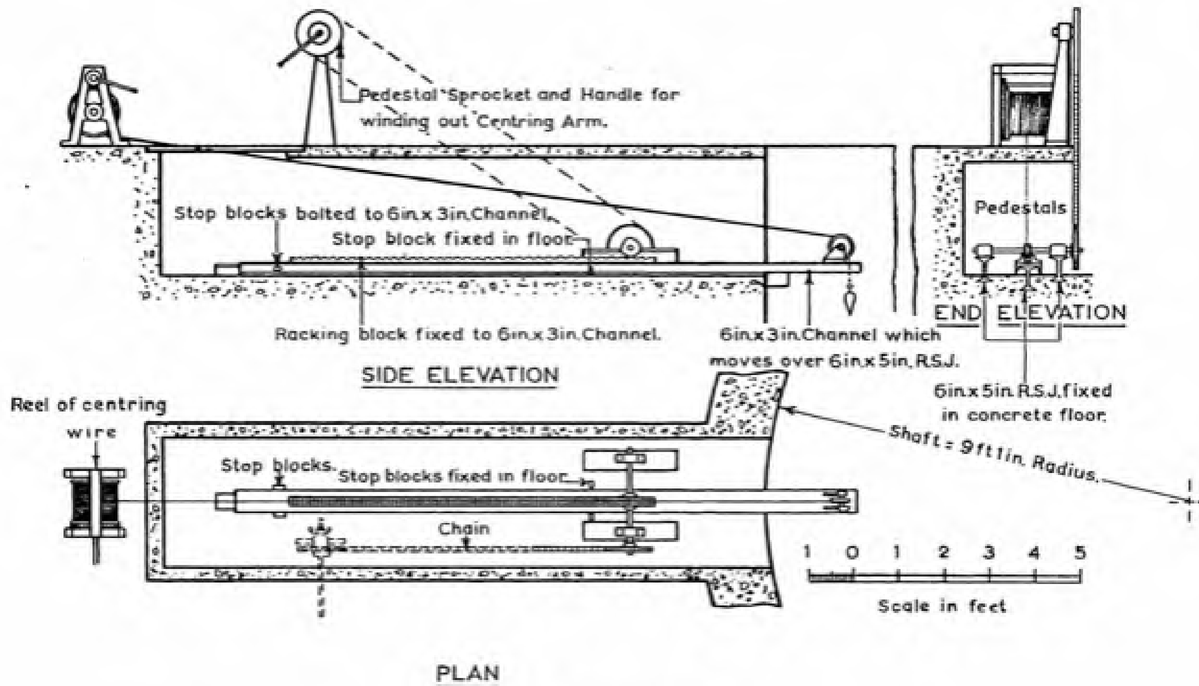


FIG. 166. CENTRE-LINE APPARATUS

The segments are reinforced by a tee-section stiffening member 3 in. × 2 in. running horizontally across the centre. The $\frac{1}{2}$ in. bolt holes on the vertical joints are on 6 in. centres, those on the horizontal joints are oval to allow a lateral movement up to $\frac{1}{2}$ in. and are on 12 in. centres. The vertical joints are butt joints between the angles with the exception of one joint from which the angle irons are omitted and an overlap of the plates substituted. Alternatively, a special angle iron with an acute angle on one plate and a supplementary obtuse angle on the other plate may be used. These special closing joints are necessary in order that the segments may be taken down later comparatively easily.

It is essential that the first ring be correctly centred and levelled otherwise the lining will not be vertical. The floor of the stonehead is levelled and each segment is placed with a sleeper under the joint between two segments the backs of which have been cleaned and greased so that the concrete will not adhere. The ring of segments is levelled up by means of two straight-edges 12 in. deep and 1 in. thick, one of which is about 6 in. longer than the finished diameter of the shaft while the other is 6 in. longer than the radius. The two straight-edges are placed at right angles, a plate on top of the shorter resting on top of the longer straight-edge. The two segments supporting the longer are adjusted to a level position by wedges on the sleepers and the remaining segments are levelled by traversing round the shorter straight-edge. The centre line is then lowered and the radius rod applied and by means of "spear wood" or struts from the side to each vertical joint, the ring is centred and is then again levelled by the straight-edges. Centring is again checked and then the levelling until both are correct.

A base for the concrete is next prepared. Small dirt with sand on top to a depth of 6 in. is placed as a level bed, all round the shaft behind the ring of segments (Fig. 167). Upon this is placed a ring of bed boards tapering from 7 in. at the back to 6 in. at the front, about 1 in. thickness and the same width as the thickness of the concrete lining to be inserted. They fit closely around the shaft and on top of them is stretched a layer of brattice cloth. The ring is filled with concrete consisting of three or four parts of broken stone or hard pebbles, two parts of clean, sharp sand and one of cement. To get a good smooth face on the wall the concrete is well rammed, but care should be taken not to cause segregation of the aggregate or to displace the ring of shuttering.

The spear wood is removed and the next ring of shuttering is fitted and bolted to the first and carefully centred. It should not require to be levelled but this should be checked. The temporary lining is

removed as the shuttering is extended. About fifteen rings of shuttering are provided, by which time the bottom shutterings may be removed as the concrete lining will have set.

If rigid guides are to be installed for cages or skips, boxes for the buntons must be left in behind the shuttering and a plumb line hung in the shaft at each side so that these may be dead in line, the boxes on one side being twice the depth of those on the other side to facilitate the installation of the buntons. Care must be taken that the boxes do not become displaced and float on the top of the concrete.

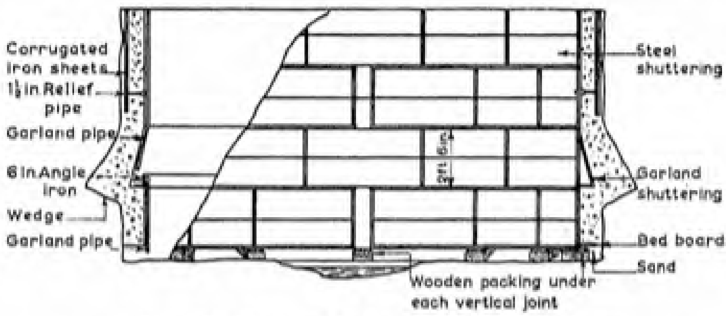


FIG. 167. WALLING CRIB AND OUTSIDE GARLAND

The lining is continued in this manner to the surface, boxes being inserted for girders, for keps and other purposes and if a fan-drift or a cable culvert is required a number of boxes are stacked to the shape of the drift or culvert. Care should be taken to give a smooth lead to the air and to avoid sharp turns and short radius bends in a fan-drift.

While the last length of lining is being placed, foundations are excavated for the headgear legs and the winding and scaffold engines. The concrete piers carrying the front legs of the headgear will be approximately 5 to 7 ft square and 6 ft deep but much depends upon the nature of the ground. The piers for the back legs are larger and finished at an angle to accommodate the rake of the back legs. The main appliances about the pit top are generally incorporated on a concrete raft or shaft block some 3 ft to 3 ft 6 in. in thickness and 40 ft × 30 ft, or thereabouts, in area. This may be tied in to the shaft lining or may be separate. If the ground is unstable and movement may subsequently occur the two are generally separate so that the shaft lining is not disturbed.

Ventilation tubes 20 in. to 24 in. diam are provided in 6 ft or 9 ft lengths with a length of canvas hose of the same diameter clamped to the bottom end of the pipes so that while air is conducted close to the

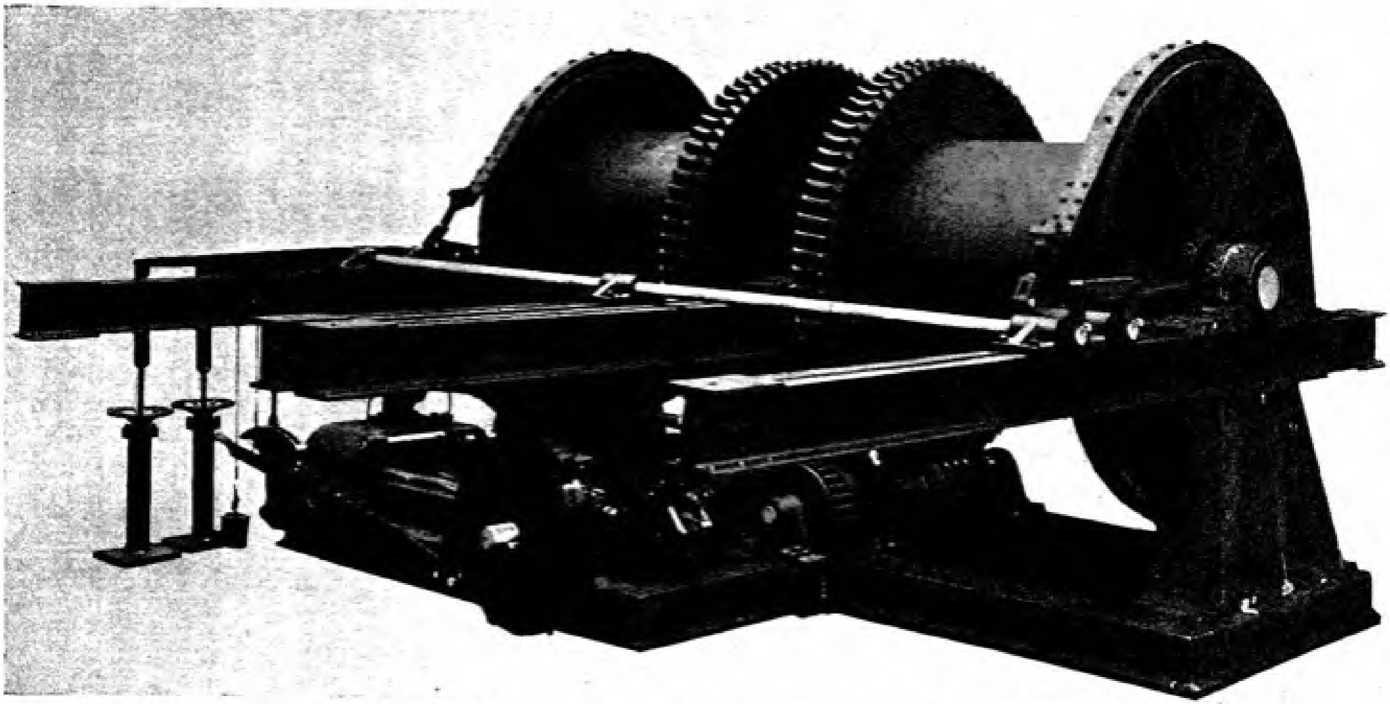


Fig. 168. Double Drum Mine-sinking Scaffold Capstans (Markham & Co.)

bottom of the shaft the ends of the pipes are not damaged by blasting. The pipes are supported by clamps of 2 in. × ¼ in. iron round the pipes at 20 ft intervals and connected by short sling chains or stays to eye-plugs in the shaft lining. The pipes are connected together by two angle lugs at each end of the pipe through which bolts pass. A forcing fan is practically always installed since the pit-bottom, where the sinkers are at work, is by this method cleared of fumes from explosives first. Axial-flow fans with a capacity of about 12,000 ft^3/min at a water-gauge of 9 in. to 12 in. are generally used, the fan being installed at or near the top of the shaft.

A column of 4 in. pipes in 18 or 20 ft lengths carries compressed air at 90 lb/$in.^2$ for drilling from an electrically-driven vertical air compressor with a capacity of 500 to 600 ft^3/min of free air. These pipes are clamped to heavy flat iron by a U-bolt, the flat iron being bent so that the ends are against the wall and are supported on rag bolts grouted into the wall. At the bottom of the pipe line is a device for connecting half a dozen drilling machines to the pipe range. One such device is shaped like the air vessel of a pump with a number of ¾ in. drilled and tapped holes to which bends and taps are fitted to take the drilling hoses. Another type consists of a tee-pipe 2 in. diam which is attached to the end of the 4 in. range and on which from six to eight valves and connections for drilling hoses are fitted.

SINKING EQUIPMENT AT THE SURFACE AND WINDING ARRANGEMENTS

It is usual to erect the permanent headgear of lattice steel, girder sections or reinforced concrete and to use the headgear pulleys to support the plough steel lock coil ropes, generally 1 in. to 1⅛ in. diam, attached to the walling scaffold. This generally entails but little alteration of the position of the pulleys from that finally adopted for coal winding.

The lock coil ropes form guides for the sinking rider which steadies the hoppet during its ascent or descent in the shaft. A winding pulley is placed in a temporary position over the centre of the shaft during sinking. The scaffold ropes are attached to a double-drum capstan or winch. These are usually steam driven unless electricity is the sole source of power provided. In this case care must be taken to guard against accidents due to power failure with men in the shaft. The capstan is generally fixed in front of the winding-engine house. The drums are from 3 ft 6 in. to 5 ft 6 in. diam and are worm-driven (Fig. 168), each drum being provided with a separate clutch and also a powerful screw brake on the worm shaft and on the drum. Arrangements are made for reversal. The gearing has a high reduction ratio

so that the scaffold travels at a very slow speed and when stopped remains stationary even if the brakes are not applied. The size of the steam cylinders is approximately 10 in. diam by 16 in. stroke, but in any case, they should be well above the work expected from them at the greatest depth.

It may be necessary to level up the scaffold periodically. When this operation is carried out, it is always the rope attached to the side of the scaffold that is low, which is raised relative to the other rope, and never the reverse since in this case, if anything went wrong, men might fall from the scaffold. The drum to which the higher rope is attached is securely braked and the clutch then disengaged. The low rope is then raised the required amount in accordance with signals on a gong and then stopped. The clutch on the other drum is engaged and the operation of raising or lowering the scaffold continued.

On the Continent, particularly if one of the special methods of sinking to be described later is required, it is usual to use separate temporary plant for the sinking. In this country it is more usual to utilize as much of the permanent plant as possible after the stonehead is reached although temporary plant may be used throughout or for the shallow part of the sinking and while the permanent plant is being erected.

In any case only one rope will be used on the winding drum as until recently it was considered that more than one hoppet in the shaft at once would give rise to danger of collision and injury to men working at the bottom of the sinking. The winding engine, therefore, is working unbalanced and, if steam driven, may have one cylinder on dead centre at starting. It is necessary, therefore, to check that the moment of the engine with only one cylinder receiving steam is sufficient to raise the full hoppet and length of rope. In other words that—

$$\frac{\Pi}{4} D^2 \times \frac{S}{2} \times P = R(W + w)$$

where D = diameter of the winding-engine cylinder in in.,

S = diameter of crank circle in ft = length of stroke in ft,

P = the mean effective pressure in the cylinder which will be about 80 per cent of the steam pressure at the engine stop valve,

R = radius of the winding drum in ft,

W = weight of loaded hoppet in lb,

w = weight of rope suspended when the hoppet is at the bottom of shaft.

In order to increase the rate of sinking, which is one of the bottlenecks in the development of a new colliery, more than one hoppet is used simultaneously in modern sinkings.

Hoppets

Generally three or four hoppets or bowks are provided into which the debris is loaded, one or more at the bottom of the shaft being filled, one being wound in the shaft and one spare. By this means there is no waiting for the hoppet to be filled, the clivy at the end of

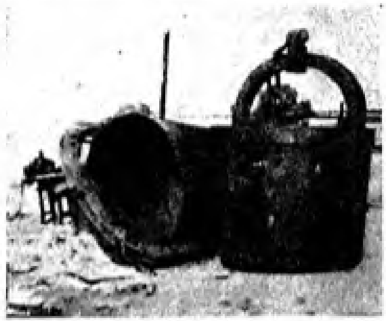


FIG. 169. SINKING HOPPETS

the rope being transferred in the bottom from the empty to a full hoppet.

The hoppet shown in Fig. 169 is 3 ft 9 in. high, 3 ft 9 in. diam at the top and 3 ft 6 in. at the bottom with a high centre of gravity when the hoppet is loaded, the axis of the trunnions coming 2 ft 5 in. below the top of the hoppet. When the hoppet is empty the centre of gravity is below the axis of the trunnions and the hoppet automatically assumes its correct position.

The body of the hoppet is formed of two curved and tapered mild steel plates $\frac{3}{8}$ in. in thickness, butt jointed, with the two trunnion plates 1 in. in thickness forming the butt straps, $\frac{5}{8}$ in. diam rivets being used. The trunnion plate and pin on each side consists of a forging from one piece of steel. The base of the hoppet is dished some 5 in. and flanged and riveted to the tapered body by $\frac{5}{8}$ in. diam rivets. The hoppet is suspended by means of a bow which fits on the trunnions, these being riveted over collars at the ends. The bows consist of two bars of mild steel, each 3 in. by $1\frac{1}{2}$ in. in cross-section, connected by 3 in. distance pieces and a mild steel single-eye forging at the top into which the bars are recessed. The forging is fitted with a 2 in. shackle and a $2\frac{1}{2}$ in. pin to which the clivy hook on the end of

the non-rotating lock coil winding rope is attached. The body is reinforced at the top by means of a beading 6 in. wide and $\frac{7}{8}$ in. thick, double riveted in position. To keep the hoppet from overturning a safety catch is fitted with a tapered pin, a catch or sneck being generally also provided on the opposite side.

Hoppet Guides and Rider

To guide the hoppet in the shaft when it is above the bricking scaffold the lock coil ropes, which are attached to the scaffold by

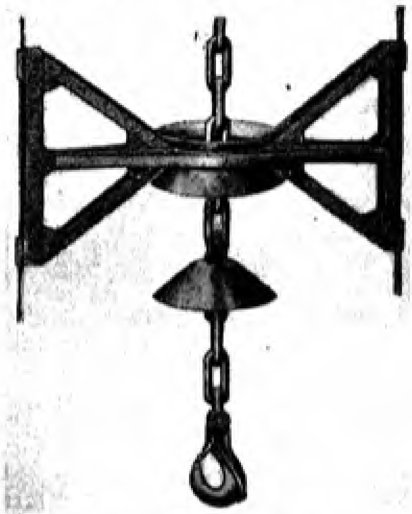


FIG. 170. SINKING RIDER (BARKER, DAVIES)

bull or bridle chains connected to four lifting irons with four eyebolts, two to each main runner, are used as guides on which a sinking rider runs (Figs. 170 and 171).

This consists of two frames of mild steel flats 4 in. × $\frac{5}{8}$ in. The vertical members are connected by distance pieces, one in the centre and one at each end, where the brass shoes which run on the guides are positioned by means of two $\frac{3}{4}$ in. bolts with split pins to prevent the nuts working loose. The vertical bars are half the distance apart of the guide ropes in length. The horizontal bars, connected and stayed to the vertical bars carrying the guide shoes, carry in the centre a double-coned mild steel plate of all-welded construction, 16 in. in thickness.

The upper cone receives the spindle which guides the winding rope when the hoppet is below the walling scaffold. The spider (Fig. 171),

consists of a brass sleeve $\frac{1}{8}$ in. greater in internal diameter than the winding rope, constructed in halves which are bolted together. To the sleeve are connected four wings of spring steel which position the sleeve in the centre of the rider cone. If an overwind occurs the

FIG. 171. SINKING RIDER AND GERMAN CAST-IRON TUBBING SEGMENTS FOR A COAL SHAFT (HEAD WRIGHTSON)

spider collapses and passes through the detaching plate or sleeve in the headgear and in no way interferes with the action of the detaching hook.

When the hoppet descends below the scaffold the rider rests on rubber buffers or springs fixed on the top of short rubber hoses threaded on the scaffold ropes (Fig. 171). When the hoppet ascends the rider is picked up by the lower cone becoming engaged by the carrier cone carried on the chain below the detaching hook. This cone consists of a mild-steel plate $\frac{3}{8}$ in. in thickness welded to a disc

of mild steel, 1 in. in thickness, carried on two forged mild steel links shaped so that the upper end can pass through two slots in the disc which is supported on shoulders on the lower halves of the limbs. The links are connected together and to the chain above and below by two strong mild-steel pins provided with nuts fitted with split pins. If for any reason the rider has to be temporarily dispensed with, such as when installing or repairing pipes in the shaft, chains are used to suspend it high up in the headgear.

The end of the winding rope is, of course, capped in the usual manner. If a lock coil rope is adopted, and this is often the case because of its non-rotating properties, either a white metal or an inter-locking wedge type of capping will be used both of which are identical with those used for normal coal winding. In addition, a detaching hook is used of the King, Humble or the Omerod type, the plate or bell for which is carried by cross girders in the headgear. This is also identical with the type used when coal winding begins.

A large D-link connects the capping with the detaching hook and this in turn is connected by long links to the rider carrier cone. Below this come a number of long links to allow long material to be lowered in the hoppet below the rider. Finally the clivy hook is attached by means of a large D-link. The hook must be designed to prevent inadvertent detachment from the hoppet but must allow quick deliberate attachment or detachment to or from the hoppet and must be of adequate strength. The hook is therefore closed by a spring or a balanced lever or tongue.

Lighting

In order to illuminate the bottom of the sinking where the sinkers are at work, a cluster of six or twelve bulbs of 50–60 candle-power with carbon filaments or traction type metallic filaments to reduce breakages is used. The cluster is arranged in an ironclad-type water-tight fitting with a shade to reflect the light down. An armour gland connects it to a two- or three-core armoured cable strong enough to support its own weight and that of the fitting. The armouring in turn is connected to the cable drum which is efficiently earthed at surface. The cores are 0·007 in.^{2} with an outer covering of rubber and has an external diameter of $\frac{13}{16}$ in. The cable is wound on a special earthed cable drum driven through gearing by a $7\frac{1}{2}$ h.p. electric motor, the cable drum shaft being fitted with insulated brass slip rings to which the cores of the cable are connected. Brushes rubbing on these rings are connected, through switchgear for cutting off the supply, to the surface lighting mains. The cable is led down the shaft over a pulley fixed in the headgear.

Shot-firing

The shot-firing cable, like the lighting cable, is self-supporting and is single or double armoured. It is of the two-core type and has an external diameter of $\frac{11}{16}$ in. The cable is wound onto a hand-operated geared cable drum with an efficient brake, generally arranged alongside the lighting cable drum. The shaft has two insulated slip rings to which the cores are connected and brushes on the slip rings connect, when firing is to take place immediately, to an exploder. The other end of the cable is attached to an ordinary shot-firing cable which, being more easily repaired than an armoured cable, preserves the lower length of the latter from damage when firing.

Signalling

Signalling arrangements must be provided for the hoppet and the scaffold separately. For the former a $\frac{3}{8}$ in. wire rope is suspended in the shaft with the lower end just above the level where the men are working. When this pull-wire is operated a hammer strikes a plate as the signal to the banksman and a push-button is operated by him to transmit the signals electrically to the winding-engine house.

For movement of the scaffold, lighting and shot-firing cables a hammer and plate is used to signal to the banksman who can transmit signals electrically to both the winding-engine and the capstan-engine house.

During shaft inspections and when the first man descends or the last man ascends the hammer and plate is then used to control the movement of the hoppet, signals being relayed by the banksman electrically to the winding-engine house.

Indicator

An indicator to show both the bottom of the shaft and the position of the walling scaffold where the rider will be picked up or left is required. This is generally of the vertical type rather than the circular clock-face dial type and must be constructed in such a manner to allow of easy, accurate adjustment as the shaft is deepened.

The hoppet must be slowed up when leaving or picking up the rider and by Sect. 66 of the Coal and Other Mines (Shafts, Outlets and Roads) Regulations, 1956, under the Mines and Quarries Act, 1954, the hoppet must be stopped 18 ft from the bottom of the shaft or above any cradle or platform upon which the hoppet or kibble is to alight and await the chargeman's signal to lower. When raising the kibble or hoppet is shall be stopped 4 ft from the bottom and steadied before being signalled away by the chargeman. The other

provisions of these *Regulations* relating to sinking should also be studied.

Sinking Pit Protection

Pit doors or some other method of protection is necessary at the top of the shaft to protect the sinkers in the bottom from objects which might otherwise fall upon them. Three systems are commonly used—(*a*) a Running Bridge, (*b*) flat doors at surface level and (*c*) flat doors at surface level and Vee or Inclined Door above.

(*a*) The Running Bridge consists of a movable platform running on rails laid on a strong frame at each side of the shaft opening. On the platform rails are also laid which connect with rails on the pitbank and upon which a Jubilee tipping wagon runs. The front of the movable platform or bridge carries a fence and the opening at the shaft is fenced round on the other three sides. When debris is being wound the shaft area is open but fenced all round. The hoppet is raised to the surface above the height of a Jubilee wagon on the bridge. The bridge is then run forward covering the shaft opening. The hoppet is tipped into the Jubilee wagon on the bridge, the bridge is run back and the hoppet is lowered into the shaft.

(*b*) When the shaft diameter is not too great, counterbalanced hinged doors may be used to cover the top of the shaft. Rails are fixed to the upper side of the doors so that when they are closed a side or end-tipping wagon can be run on to them and the hoppet tipped directly into the wagon. Fig. 172 shows such an arrangement. The doors are connected by levers and balance weights to the piston-rod of a brake engine and when steam is admitted to this engine the doors are opened. On each side of the doors is an elevated platform, fenced all round and with small platforms on which the banksman and his assistant stand when tipping the hoppet into the wagon. The wagon is then run off the doors to be tipped, the latter are opened, thus completely fencing off the shaft opening, and the hoppet descends.

(*c*) When the diameter of the shaft is too large to allow of the foregoing methods to be adopted with safety, it is usual to arrange a set of flat doors similar to these described above at surface level which complete the fence round the shaft when open, but for debris a chute is arranged at a higher level. This chute is fixed to a hinged door which is in the dotted position in Fig. 173, when the hoppet is being wound in the shaft. When the hoppet has been raised to the position shown the door and chute is thrown over, the chute on the door now forming a continuation of the fixed chute delivering the contents of the hoppet to the dirt wagon on the right. The hoppet is tipped and emptied and then raised to allow the door and chute to be

withdrawn to the dotted position. The doors at surface level and the hinged door with chute above are operated by levers and balance

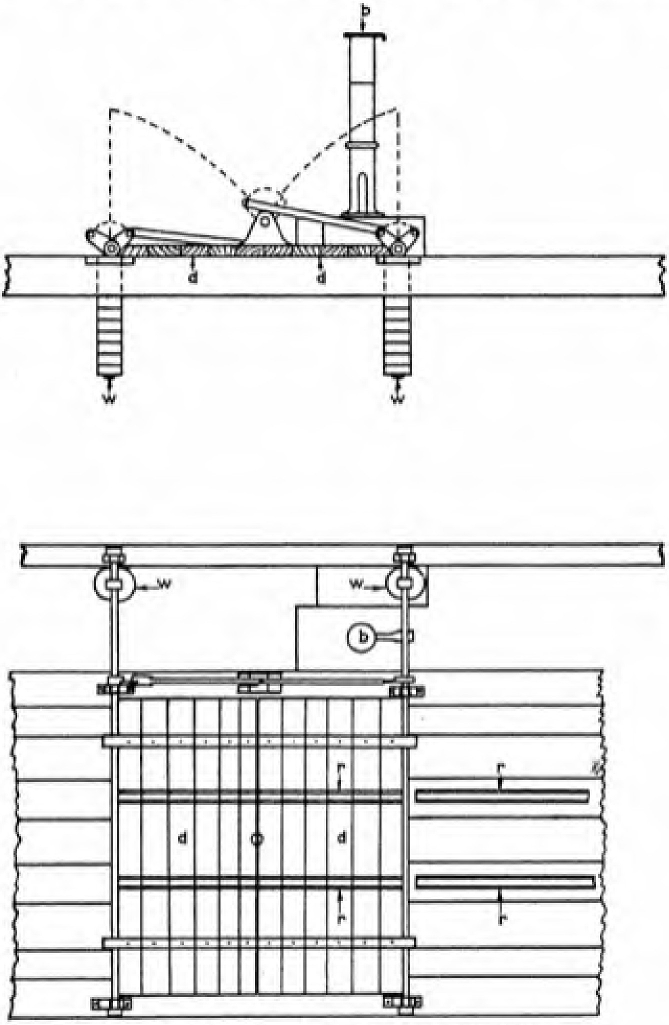


FIG. 172. FOLDING DOORS FOR SINKING

d, doors; *r*, rails; *b*, brake engine; *w*, counter weights.

weights to facilitate opening and closing, care being taken that these cannot come loose and fall down the shaft.

The actual operation of the doors is often performed by a steam or

compressed-air engine of the steam reverser type equipped with floating-valve gear and a cataract cylinder. Fig. 174 shows an alternative arrangement utilizing Vee doors which when closed form

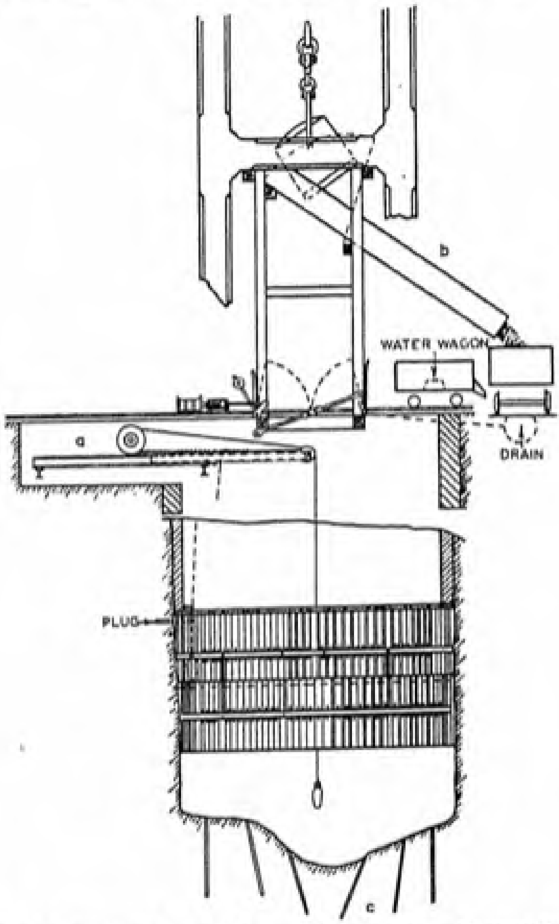


FIG. 173. ARRANGEMENTS IN AND AT THE SURFACE OF A SINKING PIT (GILL)
(a) Centre-line apparatus; (b) Chute for loading debris into wagons; (c) Round of shot-holes.

a 90° angle the one with the other. Half-round slots are cut in the doors to enable them to fit closely round the scaffold suspension ropes. A guide for the debris tipped from the hoppet when the doors are closed is fitted to one or both doors. The doors, which when closed lie at an angle of 45° to the horizontal, are supported by wooden

frames of 6 in. by 7 in. timbers and they are composed of 3 in. planks sheeted with $\frac{3}{8}$ in. thick steel plate and secured by $4\frac{1}{2}$ in. by $4\frac{1}{2}$ in. by $\frac{1}{2}$ in. angles at the ends of which the steel forged hinges are bolted. The bosses of the hinges are bored to take a $4\frac{1}{2}$ in. diam turned steel shaft, one to each door, to which the doors are keyed. Each is fitted with a lever and balance weight and the two sets are coupled together

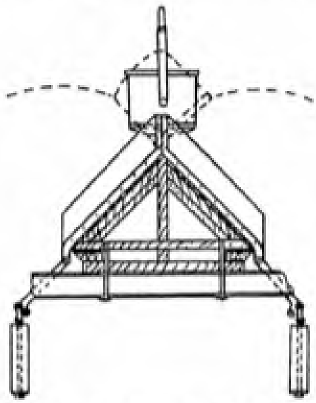


FIG. 174. VEE DOORS AT A SINKING

for simultaneous operation. The balance weights, which are clear of the shaft, are further protected by fencing.

These doors are practically invariably operated by a reversing engine. This arrangement has the advantage in that the hoppet is stopped in the tipping position and needs no further adjustment in height. It is tipped, the doors are opened and the hoppet descends the shaft again. Tipping trucks of the Muirhill type (Fig. 175), are replacing other methods for transporting the debris from the sinking to the disposal site.

Further Excavation

Assuming that the equipping of the surface is complete, sinking will be resumed. The strata below the first bricking curb is excavated on a reduced diameter for a yard or so and then gradually cut back to the full width of excavation required for shaft diameter and thickness of lining. This first length beneath the curb is carried out as far as possible with a minimum use of explosives, pneumatic picks, hammers and wedges being used. The scaffold is placed in position clear of damage by blasting in the pit-bottom and is steadied by shooting the bolts or by inserting the wedges between the lining and

the scaffold, thus steadying the scaffold ropes forming guides for the rider.

When the full width has been gained excavation is by shot-firing. The shot-holes are bored by heavy hammer drills with a consumption of 100 to 120 ft^3/min of free air, some half-dozen machines working in the bottom at one time. The drill steels are 1 in. diam with a $\frac{1}{4}$ in. hole down which a jet of air blows out the cuttings and keeps the

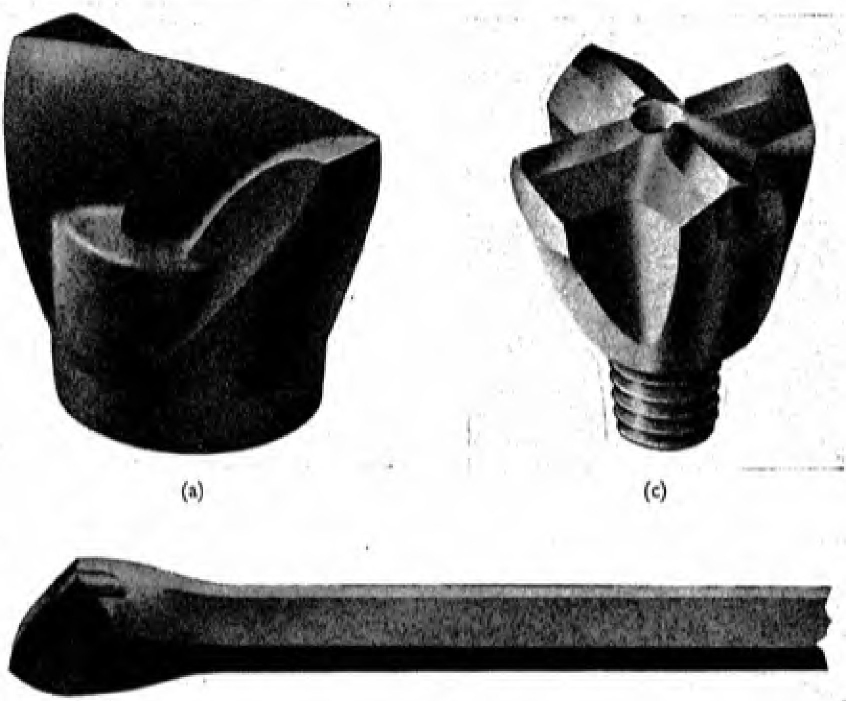
FIG. 175. MUIR-HILL TIPPING TRUCK FOR REFUSE DISPOSAL TO DISPOSAL POINT

bottom of the hole clear. In normal ground reverse Z bits, *a* (Fig. 176), are used while in hard ground chisel-edged bits, *b*, may be adopted. The drill steels are in sets of four, 20, 40, 60 and 80 in. in length. Jack-bits are now very often adopted in sinking, both hard-steel alloys and tungsten carbide tips being used.

The inner ring of holes, known as the "sumpers," are bored on a circle of about 10 ft diam and all holes are inclined towards the centre of the shaft so as to lift out a cone of material when fired. The holes are bored to a depth of 6 to 7 ft and they are approximately 2 ft 6 in. apart in normal ground. The sumpers are usually charged with 28 oz of Polar Gelignite or more.

The next ring of holes on a circle 15 ft in diameter are less inclined to the centre of the shaft, i.e. nearer the vertical, as they have a free face produced by the firing of the sumpers. The next ring, known as the side holes, are bored vertically practically on the edge of the

excavation required in hard rock and a short distance away, to avoid fracturing the sides, in softer strata. Fig. 177 shows typical shot-hole patterns in hard and soft ground. Each ring of shots is fired simultaneously, low-tension detonators being used and the firing cable is tested periodically with a galvanometer for continuity. Delay



(a) (c) (b)

FIG. 176. TYPES OF DRILLING BITS

(*a*) Reverse z; (*b*) Chisel-edged, with tip; (*c*) Jackbit with tips.

action detonators may be used in sinking pits in accordance with Sect. 27 of the *Coal Mines* (*Explosives*) *Order*, 1956. Any irregularities remaining after firing are dressed off by hammer and wedge or by pneumatic pick.

Explosives used for sinking are non-permitted explosives and the exploder provided must be of a type approved by the Ministry of Fuel and Power. If the exploder is of the rackbar type a small direct current armature is caused to rotate at high speed, at the end of the stroke a contact is closed and current flows in the circuit through

the low tension detonators connected in series. The capacity of the exploder should be such that it is capable of firing fifty shots in series with a voltage of 180 and a current of three amps. Various other types of exploders are also available including those in which shots

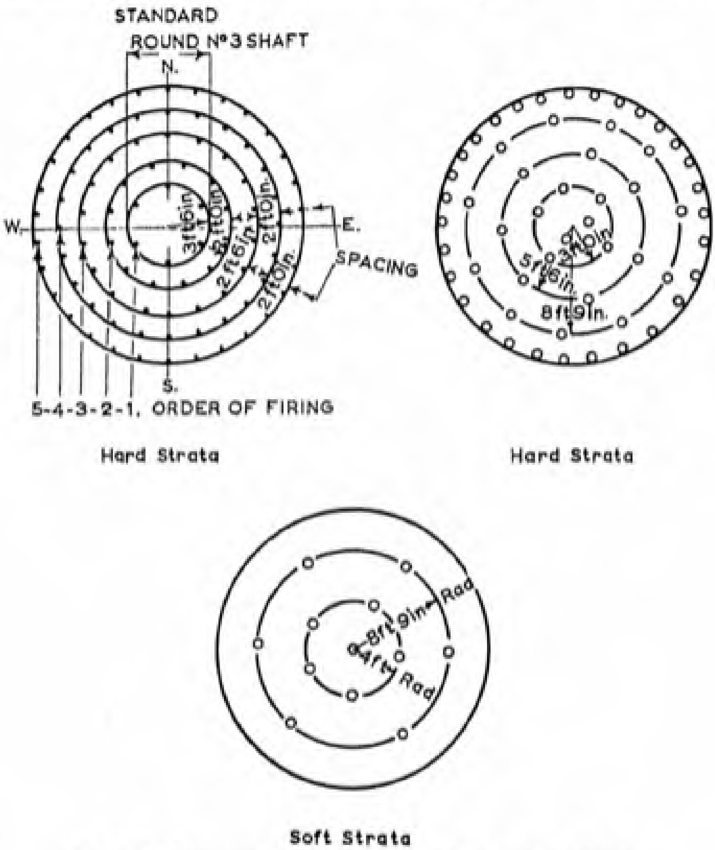


FIG. 177. SHOT-HOLE PATTERNS IN HARD AND SOFT STRATA

are fired by discharging a bank of condensers charged to a high voltage.

The debris after firing is loaded away into hoppets and temporary supports are inserted. The first ring is supported on plugs driven into the side, or if a concrete curb has been inserted for the lining above, holes are bored in the curb some 2 ft from the bottom of the wall and plugs inserted of $1\frac{1}{2}$ in. round iron, 12 in. to 18 in. in length, pointed at one end and turned up for 6 in. at the other end. From

this a chain is hung which supports a segment of the first ring, each segment having its own plug. The second and third rings are hung by hangers from the first ring and in normal ground plugs are then inserted to support the third ring. The sixth ring is, in a similar manner, supported at first from above and then on its own plug supports. The distance sunk and temporarily lined before the next curb is inserted and the lining carried up depends on the strength of the ground and may be 60, 75 or even 100 ft. If, however, weak ground is encountered the walling up of this portion is carried out earlier and it is secured as quickly as possible.

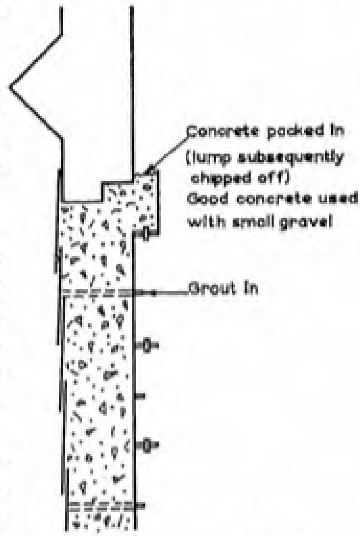


Fig. 178. Grouter Ring

The curb for a brick lining is inserted in exactly the same way as the first curb and the lining, generally 9 in. brickwork, is carried up to the wedge-shaped ledge of strata supporting the top curb. This may be built into the wall or the strata supporting the top curb may be removed piecemeal and replaced by brickwork. If the ground is very weak a lower curb may have to be supported on plugs. These are iron or steel rods several feet in length driven into holes in the strata so that about 2 ft of rod projects.

Where a concrete lining is adopted the concrete curb is first put in followed by the falsework for the lining and this is continued until the curb above is reached. At this point instead of the usual plates 2 ft 6 in. in height a ring 2 ft or 12 in. or 6 in. in height is used. This is known as a "matcher" ring. The 6 in. matching ring is similar to a channel section, 6 in. × $2\frac{1}{2}$ in., in lengths of 3 ft and is curved to the radius of the shaft.

The wall is brought up to within a few inches of the top curb by using some or all of the matching rings enumerated and on top is fixed the "grouter" ring (Fig. 178). This consists of a $2\frac{1}{2}$ in. × $2\frac{1}{2}$ in. angle iron bent to the radius of the shaft but fixed in the reverse manner to the falsework rings. The perpendicular side of the angle is thus $2\frac{1}{2}$ in. towards the centre of the shaft. To this is riveted a plate 12 in. in height. A fine grout of Whin sand and cement is poured in

here in a sufficiently fluid state to allow it to flow underneath the top curb, the base of which is scoured up to ensure a good joint. The grouter ring is filled to the top to give a small vertical head to prevent voids and to force the grout well back all the way round. When the concrete has set the plates are removed leaving a few inches of shaft 5 in. less in diameter where the grouter ring was placed. This is dressed off with a hand or pneumatic pick.

Water garlands will be required in the lining to collect water in the shaft. They are constructed in a similar manner to a curb. The

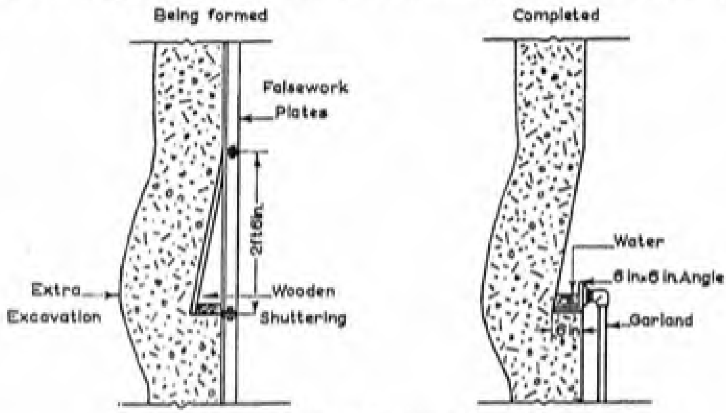


FIG. 179. WATER GARLAND (DOWNIE)

excavation is widened all round to a depth of 1 ft (Fig. 179). Wooden shuttering to the width of the garland required is fixed against the shuttering to give the required shape. The garland itself may consist of 6 in. × 6 in. angle iron curved to the radius of the shaft and fishplated together with countersunk bolts on the inside.

Arrangements for Dealing with a Small Quantity of Water in Sinking Pits

If only a small quantity of water is encountered in sinking a pit it may be ladled into hoppets, wound in the ordinary way and discharged into the surface drainage. In order to pick up water without making sumps in the pit-bottom water barrels may be used which produce a vacuum and draw the water into the barrel. These are of two types (*a*) Piston type, (*b*) Vacuum type. Both are attached to the winding rope instead of the hoppet.

(*a*) The Piston type of barrel consists of a mild steel circular tank 4½ ft diam of 800 gal capacity. It is fitted with a piston to suit the internal diameter of the barrel, the piston being provided with 6 in.

India rubber disc valves. The piston rod, 3 in. square, has a stroke of 8 ft 4 in. and is attached directly to the winding rope, sliding through a cast-iron guide block mounted on the top of the barrel. At a point 10 in. from the top of the barrel nine $\frac{3}{4}$ in. holes are drilled as air inlets to increase the speed of water discharge. The system operates in the following manner—the barrel, full of water when it reaches the surface, is lowered into the water wagon run onto the doors covering the sinking. The water inlet valve stem, which protrudes underneath, strikes a fixed block in the bottom of the water wagon and the valve is raised off its seat and the contents of the barrel are discharged into the wagon and from this into the surface drainage. The barrel is then lowered into the pit. When the depth of water in the pit-bottom is less than the height of the barrel, the latter is lowered on to the bottom with sufficient slack in the winding rope to allow the piston to travel to the bottom of its stroke. On tightening the rope the piston is raised and atmospheric pressure forces water into the barrel in which it is retained by the bottom valve.

(*b*) In the Vacuum type the tank has a capacity of about 300 gal and is closed at the top. It is fitted with a water inlet valve at the bottom and a tube enters the side of the tank and is bent vertically reaching nearly to the top of the tank. The external end of the pipe carries half of a vacuum coupling. A vacuum pipe is taken down the shaft from an air pump on the surface. At the bottom the pipe carries a short flexible hose terminating in the other half of the vacuum coupling. When the barrel is lowered into the pit-bottom the coupling is connected, air is exhausted from the barrel and water flows in through the inlet valve. A water gauge is fitted to the barrel so that it may be seen when this is filled. The coupling is then disconnected and the tank hoisted to the surface.

Speed of Sinking

Formerly the permanent winding engine was used for hoisting debris with one hoppet only in the shaft. This method has now been largely superseded. With shafts of 24 ft diameter and depths of the order of 1,000 yd, equipped with rigid girders to reduce clearances to allow four cages in the shaft, temporary winding engines for sinking only, working with two hoppets and dual-single winders, are being used.

The record for sinking a circular shaft in South Africa is 743 ft per month attained in October, 1955. In this country in March, 1955, at the Cynheidre sinkings in the Anthracite area of South Wales the No. 1 shaft was sunk for a distance of 222 ft 7 in. and lined for a distance of 158 ft 1 in. In the same month the No. 2

shaft was sunk 238 ft 9 in. and lined for a distance of 140 ft 10 in. The overall distances sunk and lined per day for a seven day week were: No. 1 Shaft 4 ft 1 in., No. 2 Shaft 4 ft 10 in.

In the first quarter of 1957 at Bevercotes No. 2 Shaft the average distance sunk and lined per month was 150 ft.

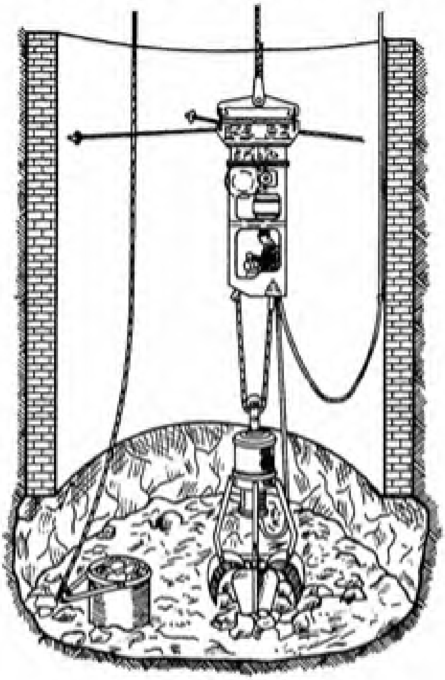
Mechanization

Sinking frames for supporting hammer drills, such as the Walker, have been used in sinking for a number of years but do not seem to have had any very wide application; but as accurate hole positioning is important, positions may be indicated by means of a device pivoted on a centre pin equipped with a universally jointed arm and drill-guides to position the outer and inner holes. Chains suspended from the arms indicate the position of the intermediate holes. Drilling takes place in a definite pattern and all machines start and finish at the same time.

For the loading of debris the restricted space available limits the choice of mechanized loading equipment. At present the Eimco 621 crawler-mounted rocker shovel, the larger Eimco 630 and the cactus grab are the only loading equipments being used with success. The last equipment is the one most generally used. This has been used in this, and in many other countries, particularly in South Africa, and on the Rand the "Octopus" (Fig. 159) has been used to place concrete quickly behind shuttering in concrete-lined circular and elliptical shafts. The octopus shown has a capacity of 2½ cu yd, and has ten 6-in. or 8-in. diam. pipes welded into the base. From these the concrete is delivered by 6½-in. to 8½-in. diam. rubber hoses behind the shuttering all round the shaft periphery. The octopus was at first clamped to a pair of guide or scaffold ropes on one side of the shaft on which also rode a 2½-cu yd capacity Blaw-Knox concrete bucket of the bottom-discharging type. After discharging its load of concrete in 15 to 20 seconds the bucket was hoisted to the surface and again filled with concrete from a 2½-cu yd capacity concrete mixer through a hinged chute. Further developments have been the installation of the octopus permanently on the top of a three-decked scaffold or stage (Fig. 180B) to be followed by the substitution of a 6-in. or 8-in. diam. pipe from the surface instead of the bucket for the lowering of concrete in the shaft.

The grab has been used extensively to increase the speed of sinking, particularly of circular shafts which are increasing in popularity in South Africa, at the expense of rectangular shafts which were previously preferred. The rectangular shape is unsuitable where the strata is weak or heavily water-bearing and the increasing price

and difficulty of obtaining suitable timber and higher maintenance costs have reduced the economic advantage of timbered shafts. The greater resistance they offer to the heavy ventilation requirements, because of greater depth and steeper geothermic gradients, empha-



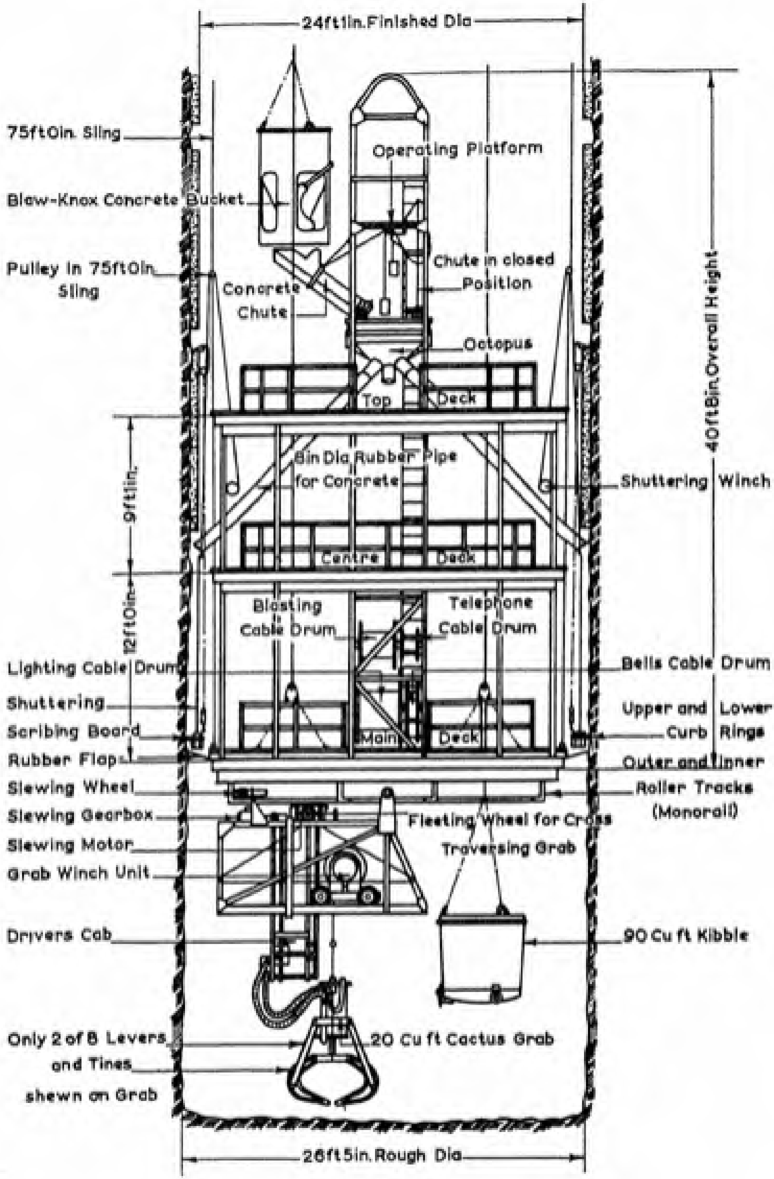
(a)

Fig. 180A

sizes the advantages of lined, and particularly of smooth concrete-lined, shafts.

Previously, one of the disadvantages of the concrete-lined circular shaft compared with the rectangular timbered shaft was that sinking operations had to be stopped while the concrete lining was being poured, a curb ring being set on the bottom of the shaft and shuttering, brought down the shaft in small sections from the surface, erected on it. Concrete was then poured between the shuttering and the shaft walls to form a lining in from 30- to 60-ft lengths. The shuttering then had to be dismantled and wound in sections to the surface.

In the relatively strong rock sunk through in South Africa it was found possible to suspend a curb ring from chains some 30 ft above


24ft1in. Finished Dia
75ft0in. Sling
Operating Platform
Blaw-Knox Concrete Bucket
Chute in closed Position
Pulley in 75ft0in Sling
Concrete Chute
Octopus
Top Deck
40ft8in. Overall Height
9ft1in.
8in Dia Rubber Pipe for Concrete
Shuttering Winch
Centre Deck
12ft0in.
Blasting Cable Drum
Telephone Cable Drum
Lighting Cable Drum
Bells Cable Drum
Shuttering
Scribing Board
Upper and Lower Curb Rings
Main Deck
Rubber Flap
Outer and Inner Roller Tracks (Monorail)
Slewing Wheel
Slewing Gearbox
Fleeting Wheel for Cross Traversing Grab
Slewing Motor
Grab Winch Unit
Drivers Cab
90 Cu ft Kibble
Only 2 of 8 Levers and Tines shewn on Grab
20 Cu ft Cactus Grab
26ft5in. Rough Dia

(b)

FIG. 180B

the bottom of the shaft thus leaving the shaft bottom clear for sinking to proceed while walling was taking place. When the concrete had to be lowered down the shaft in bottom-emptying buckets and only a single winding rope was available this could only proceed during drilling and charging shifts when the winding engine was not winding sinking debris. A further recent development has been the transport of concrete down the shaft in a 6-in. or 8-in. vertical pipe mentioned above, the concrete being generally a mixture of 4½ parts of sinking rock, crushed to below 1 in., to one part of cement, 5 per cent of calcium chloride being added to promote rapid hardening of the concrete and a plasticizer, "Lissapol," to ease the flow rate. All the sinking and walling operations are integrated so that they do not interfere one with another; the time taken to lower and reset the shuttering has been reduced to a minimum and the 30 ft of lining can be placed in 32 hours, four hours less than the time required to sink this distance, which can be devoted to extending and fixing air, water and concreting pipe columns. In using a stage and moving concreting shutter in this manner the placing of shot-holes must be very accurate as small protrusions left after blasting may be sufficient to foul the stage or shuttering and cause serious delays.

Both in South Africa and in this country mechanized methods of loading sinking debris into hoppets are being increasingly adopted for the following reasons—

1. In certain instances the winding facilities available exceed the loading capacity of the maximum number of sinkers who can conveniently be accommodated in the shaft bottom, and the hoppet which can be raised by the winding-engine power available exceeds 3 or 4 tons and in consequence becomes unduly high for filling by hand with comfort.

2. Shortage of labour in both countries encourages the mechanization of all possible operations.

3. Interruptions to the normal rate of sinking may result from difficulties due to water or very weak ground, and a large proportion of hand-loading sinking crews is, of necessity, temporarily redundant.

4. In most cases it is considered that mechanical loading will increase the speed of sinking and that the cost of sinking is in inverse proportion to the speed of advance when interest and amortization of capital tied up in development is included. In a typical South African mine it is calculated that a reduction of one year in the development period, as a result, among other factors, of an increased rate of sinking, will enhance the present value of future distributable profits by £½ million. A similar result obtains

in the case of the development of a large new colliery and in both cases considerable expenditure is justified in the provision of equipment for this purpose. Since the productive capacity of British collieries is wasting and needs replacing at the rate of 4 to 5 million tons annually in addition to the annual increase in production visualized in the National Coal Board's "Plan for Coal" and "Investing in Coal," the provision of such equipment, which can be transferred to successive new sinkings, is an attractive proposition.

Three methods of operating the grab have been successfully applied. The type of grab adopted is the cactus type with six or eight claws or tines tipped with tungsten carbide with an approximate capacity of one ton of material (Fig. 180A). The jaws are operated by a double-acting compressed-air cylinder and the grab is raised or lowered, traversed across or slewed round the shaft by compressed-air motors, providing access to any part of the shaft.

When the pile gets below 6 in. to 9 in. the grab has difficulty in filling. Usually the last 6 in. at least is filled by hand—often taking the better part of a shift. This is one reason why the Eimco 621 can compete with the grab. Although it has a low loading rate at "peak loading" it can clean up completely and avoids the slower hand-mucking. At Bevercotes and Cotgrave in Nottinghamshire a combination of the two are used; the grab loads the main part of the pile and the Eimco 621 is then slung in to load the last foot or so.

In the arrangement of equipment shown in Fig. 180B that at Valkfontein No. 2 shaft of New Consolidated Goldfields, Ltd., of South Africa, the grab unit is suspended from a mono-rail carried under the bottom deck of the three-decked sinking scaffold. Seven natives only are employed in the bottom to detach and attach hoppets, level off and steady them, and one to pump the small quantity of water made during sinking.

The shaft has a finished diameter of 24 ft 1 in. and a depth of some 6,900 ft. The lining is of concrete 18 in. in thickness in 11-ft lengths, in this case with annular spaces between of 18 in. to take buntons which will be filled in when these are installed. The main winding engine is Ward Leonard controlled and of 3,700 h.p. with double drums 16 ft in diameter and ultimately $1\frac{7}{8}$-in. diameter non-spin ropes. The hoppets carry 5 tons and the Blaw-Knox concrete buckets 3 tons.

The four-drum sinking scaffold hoist is 225 h.p. and the ropes $1\frac{3}{8}$ in. in diameter, two right-hand and two left-hand lay. A petrol-driven 500-V generator is installed to supply power to move the scaffold in the case of failure of the main power supply.

The three-decked sinking scaffold weighs 45 tons; the top deck

is used for installing pipes and for delivering concrete to the Octopus through the hinged chutes from the Blaw-Knox buckets. The middle deck houses the winches for lowering the concrete shutter and six 150-watt lights, and is used for stowage of hoses and supervision of concreting operations. The bottom deck carrying the grab unit is suspended from the four scaffold ropes and six 75-ft rope slings from the lining above and carries four pneumatic jacks to steady the scaffold by thrusting against the shaft periphery, there being a 9-in. clearance between the scaffold and the shaft walls bridged by rubber flaps. It also carries the cable reels for shot-firing, lighting, signalling and telephoning and three 500-watt floodlights.

The stage is raised during blasting operations and after these are completed and the fumes have been cleared by the 50-h.p. fan and the 40-in. diameter steel ventilation pipe-line in about 15 minutes, the stage is examined for damage and then lowered until the six sling ropes are taut. The lower hanging curb is then positioned as required at a distance between 38 and 48 ft of the shaft bottom. It is supported by twelve chains, six 25 ft long and six 37 ft 6 in. long, fitted with turnbuckles for centering and levelling accurately which is checked by means of four 200-ft steel tapes and four plumb lines at the shaft sides. The scribing boards are then cut by a power saw and inserted. The 11-ft high moving concreting shutter is then lowered by the hand winches on the middle deck, the $\frac{7}{8}$-in. diameter ropes being threaded through pulleys carried by the wire slings steadying the scaffold. The shutter tapers from 24 ft 0 in. at the top to 24 ft 2 in. at the bottom to ease lowering and is collapsed by removing two locking pieces in the periphery. When lowered into position the locking pieces are replaced and the shutter expanded back to its full diameter.

Nine men are employed on the scaffold in this operation during which loading is proceeding 30 or so feet below, both hoppets being engaged on raising sinking debris. At the end of the drilling period while the holes are being charged a further eight men from the drilling crew of 41 assist on the scaffold. Concrete is distributed from the octopus to six 8-in. diameter hoses during the end of the loading and the drilling period, long-handled shovels and two pneumatic vibrators being used to compact the concrete. The hoses are manipulated with the aid of the six winches used to lower the shutter into position. After loading out of debris from the bottom of the shaft has been completed both winding ropes are used for the Blaw-Knox concrete buckets and the concrete shutter is filled in a period of three hours.

Ten men do the charging in the shaft bottom, 140 shots

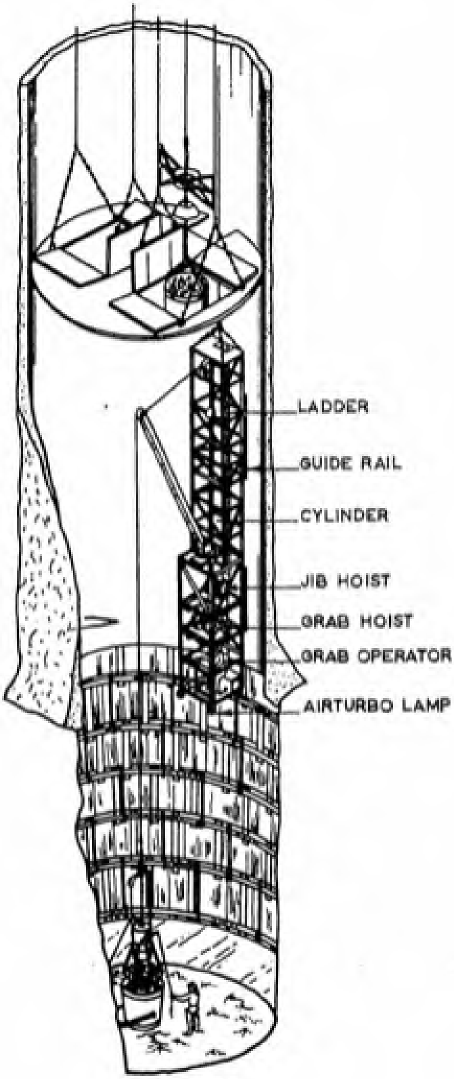
aggregating 300 to 350 lb of gelignite, water stemmed, being fired, wax primers being used with half-second delay detonators, the primers being already wired up on the surface in two batches in the form of a "harness" so that only two outer leads require to be joined and then coupled to the shot-firing cable.

Immediately before firing the scaffold is raised 150 ft up the shaft with fourteen men who lift side and pipe flaps and fend the scaffold off the sides and pipes. The firing circuit is tested from the scaffold and the men then ascend to the surface in the hoppets. Firing is from a special mains switch cabin on the surface which is kept locked with the key in the possession of the white shift boss until all men are checked out of the shaft.

The second type of grab equipment, which is preferred in British practice, is mounted in a frame attached to the concreted shaft wall above the bottom of the shaft but connected with a separate single rope capstan at the surface so that it may be raised in the shaft independently of the scaffold (Fig. 180C). The jib and the grab are controlled by separate hoists by the operator in his cabin. The jaws of the grab are tripped by a man in the shaft bottom. This type of equipment has been used at the Cynheidre and Abernant sinkings in the anthracite coalfield of South Wales.

One of the drawbacks of the mono-rail method of mounting the grab beneath the sinking scaffold is that free movement of the hoppets up and down the shaft may at times be obstructed and at best two hoppets only can be used. A new type of grab control equipment has been installed by the Anglo-American Corporation at two Orange Free State sinkings which is more flexible and allows four hoppets to be used (Fig. 180D).

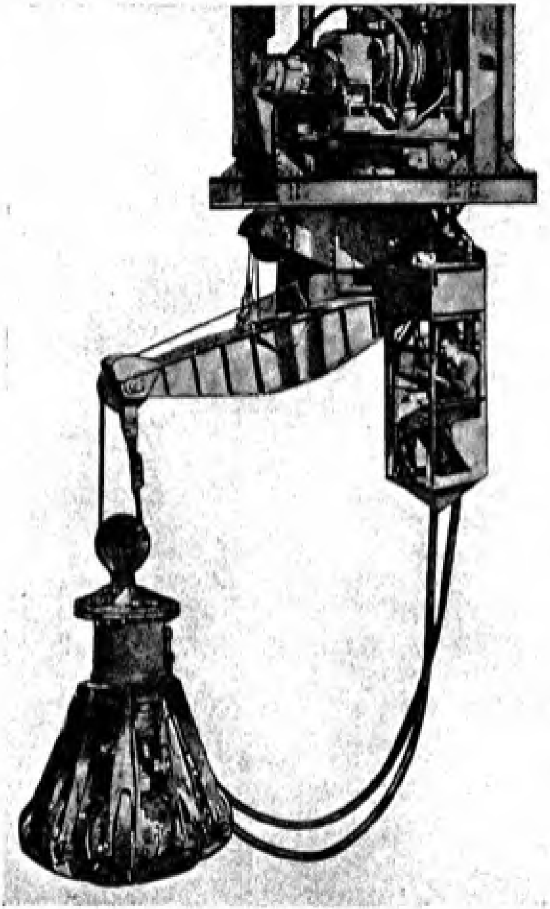
The Blair grab is suspended from a jib pivoted at the centre of the underside of the scaffold which can be luffed round through a full circle and enables the grab to pick up from any point in the shaft-bottom. The jib is lowered when the grab is operating in the centre of the shaft and raised when working near the periphery. The grab is arranged "to fail to safety" since it is driven by a double-drum winch which is running continuously when loading is in progress. Dead weights hold the clutches off and the brakes on, so that to operate the grab the driver must engage the clutch and release the brake. If he releases the controls the grab stops automatically. The grab is controlled electrically, all the driving mechanism and electrical equipment is housed on the bottom deck of the scaffold and protected by it when the scaffold is raised when blasting. The jib and grab, not protected by the bottom deck, are of heavy construction to resist damage.


LADDER
GUIDE RAIL
CYLINDER
JIB HOIST
GRAB HOIST
GRAB OPERATOR
AIRTURBO LAMP

(c)

Fig. 180c

Experience has proved that shots fired by short delay detonators give a flat plateau-shaped heap of debris which is more easily handled by mechanical grabs than a cone-shaped heap. Good



(d)

Fig. 180d

fragmentation is also necessary and pieces should be below 12-in. cube if possible.

The number of miss-fires in South African sinkings has caused some concern and experiments are being conducted in the use of instantaneous "Cordtex" fuse for interconnecting shots.

Four-drum 40-ton scaffold winches are standard equipment at all N.C.B. sinkings where double-hoppet or dual single-hoppet winders are in use. Where four separate drums and ropes are used to raise, support and lower a sinking scaffold it is difficult to keep the tension in the ropes equal even with separate clutches to each drum. Scaffold ropes have, therefore, been used in double purchase, attached to the headgear taken round a pulley mounted on the scaffold and then up the shaft, over a headgear pulley to one of two drums. This allows two hoppets to be operating in the shaft at one time and the scaffold capstan can run at double the speed when four individual ropes and drums are used.

At Vaal Reefs sinking where a grab unit was used for loading debris, two ropes were used in triple purchase each being anchored to the scaffold, taken over a pulley in the headgear, then down the shaft round a pulley mounted on the scaffold and back up the shaft over the headgear pulley to one of the double drums.

In order to support heavier scaffolds and allow more hoppets to be used simultaneously in the shaft the Anglo-American Corporation propose to use two ropes in quadruple purchase giving eight ropes which can be used as guides for four hoppets in the shaft and reducing the size of rope required. The rope is attached to the headgear, passes down the shaft round a pulley on the scaffold, up the shaft round a pulley in the headgear, down the shaft, round a second pulley on the scaffold, up the shaft and over a headgear pulley to a surge or friction wheel.

This Blair system also substitutes a surge wheel similar to that used on an endless rope haulage as a friction winder in place of the conventional drum. The rope makes $3\frac{3}{4}$ coils round the surge wheel and then passes over a pulley to a sliding pulley acting as a gravity tension and then over another pulley to a rope storage drum. The tension in the rope is at this stage reduced to a low figure and this storage drum may be of relatively small diameter without damage to the rope. When the friction winder is operated to raise the scaffold, the tension weight on the tension pulley descends and closes an electrical circuit and starts up the rope storage drum which runs faster than the friction winder and winds in the surplus rope, at the same time raising the tension weight which then completes a second circuit which stops the storage drum.

When the scaffold is being lowered the storage drum pays out rope, the tension weight acting in the reverse manner.

The present rates in sinkings in this country reach 50–60 yards of finished work per month over relatively short periods of sinking. These rates are at present achieved with "non-simultaneous"

working, i.e. sinking a length of up to 80 ft then stopping sinking to wall up that length. The simultaneous process overlapping the walling and sinking operations (either fully or partially) is now being applied to a number of shafts in this country. The application of the "simultaneous" method to conditions in this country requires that a number of problems arising from strata conditions and regulations should be overcome. It appears that such problems can be overcome at least to the extent where an average of 60–70 yards per month should be maintained over the total depth of the shaft.

QUESTIONS

1. Discuss the various considerations to be taken into account in deciding upon the site and form of mine shafts.

2. Describe the chief items of equipment in sinking a colliery shaft of 20 ft finished diameter to a depth of 600 yd. The make of water is normal and there are no unusual features.

3. Describe apparatus for determining accurately the centre of a shaft and indicate how this equipment is used.

4. Make a drawing of a bricking scaffold for a sinking pit, designed so that the scaffold ropes act as guides for the hoppet. Show how the scaffold is held in position in the shaft when the hoppet has to pass through it during sinking operations.

5. Describe a method of temporarily lining a sinking shaft, 22 ft in diameter, through moderately strong ground.

6. Describe the different forms of permanent linings which can be used in a circular shaft sunk through ordinary coal measures.

7. Describe with sketches how concrete may be used to form the permanent lining of a vertical shaft. Indicate any precautions to be taken when inserting the lining in monolithic form.

8. Describe with the aid of sketches, the arrangements which can be employed to deal with water at a sinking pit in circumstances where a special method of sinking has not been adopted.

9. Describe the apparatus which may be used in sinking shafts using mechanical aids for loading out the broken material.

CHAPTER XIV

DIFFICULT SINKINGS

As sinkings proceed away from the outcrop of seams the ground encountered in sinkings has a tendency to become (*a*) unstable, (*b*) excessively water-bearing or (*c*) a combination of the two as in Holland and the Ruhr. The original methods of overcoming these difficulties in shallow shafts were by (*a*) pumping, (*b*) piling and (*c*) drop-shaft or caisson methods. While these are still employed, for deeper sinkings they were superseded successively by the Kind-Chaudron and Honigmann boring methods, freezing and cementation.

Piling

Both wooden and steel piles may be used, the latter usually of the interlocking type. Where wooden piles are used the sinking is generally done in 15 ft maximum lifts with a constantly decreasing diameter to allow for the thickness of the piles, which are generally 6 in. × 3 in. in cross-section. At times in order to avoid loss of diameter a forepoling system is adopted in which the piles are driven at an angle. Details of shaft sinking by the piling system are given in *Trans. Inst. Civ. Eng.*, "Shaft Sinking of the Horden Colliery, SE. Durham," 1907–8, Pt. III.

Where steel piling is used much longer lifts are taken reaching 80–90 ft. The type of steel pile used at Hatfield Main Colliery, South Yorkshire, to sink through 62 ft of sands and clays is shown in Figs. 181 and 182. It consists of Universal Joist Steel Piling 15 in. × 6¼ in. weighing 39½ lb per superficial foot. The piles were driven by a 30 cwt pile driver which ran on circular rails round the piles. These were driven clockwise then anticlockwise to prevent the piles leaning from the vertical. The distance driven for each round of the pile driver varied from 5 ft at the top to 2 ft for the last stage in hard ground.

Drop Shaft and Caisson Methods

These methods consist in the use of a cutting shoe on the bottom of a shaft lining which is being continually augmented as the shoe descends, the material inside the lining being excavated. The methods

are applied in loose, unstable strata at no great depth, to about 200 ft, and three sub-divisions are to be distinguished—

1. Drop shafts in which the shaft lining sinks by its own weight supplemented if required by loading at the top.

2. Drop Shaft and Pressure ring. The weight of the lining is

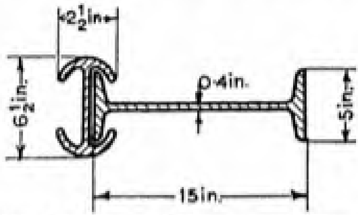


FIG. 181. SECTION OF INTERLOCKING STEEL PILES

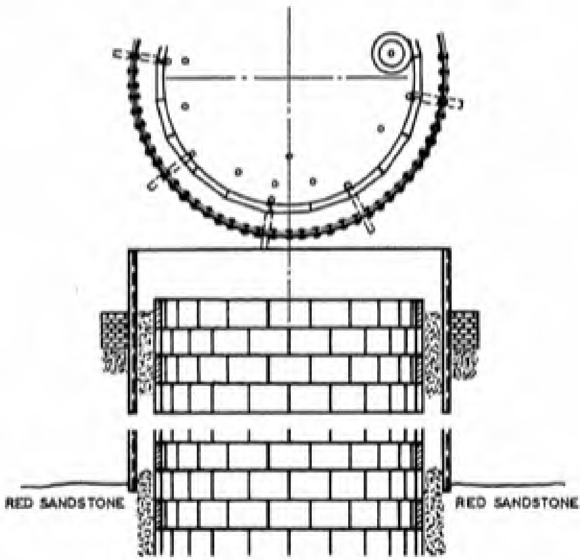


FIG. 182. SINKING BY PILING (GILL)

supplemented by the use of hydraulic jacks between the top of the lining and the pressure or anchor ring.

3. Caisson Sinking. Water and running Strata are kept at bay by pneumatic pressure and men, materials and debris must pass through air locks.

The two main difficulties experienced with these methods of sinking are maintaining verticality and overcoming the skin friction to

enable the sinking to proceed. Difficulties are increased when the strata penetrated changes in a short distance.

The first method is only applicable when the skin friction is low. If some tough beds are likely to be encountered hydraulic jacks and a pressure ring will be required. Where the ground is fluid, such as water-logged quicksand or mud, artificial pressure in the form of compressed air is required to prevent the fluid material flowing into the shaft so that in these cases Caisson sinking is necessary. To reduce skin friction, lubrication by compressed air, steam or water through holes in the lining, may be required, the last generally being preferred. The amount of skin friction is reduced with the diameter of the shaft but the shaft must generally be sunk oversize to allow for possible deviation from the vertical.

1. Drop Shafts

In drop shafts the lining is often of reinforced concrete, eight segments to the circle. It is built up behind shuttering of steel plate ¼ in. in thickness connected by 1½ in. angles, each ring being 3 ft in height. In the case of Chislet Colliery, Kent, the lining was 12 in. in thickness and reinforced and was lowered under control of eight wire ropes attached to temper screws on the surface. The sand was removed by a 5-ton loco-crane and a grab.

2. Drop Shaft and Pressure Ring

In the application of this method, which has the advantage of reducing the liability of subsidence of the surface, where a strong stratum occurs at the surface and is succeeded by unstable ground below, the strong strata is excavated by ordinary sinking methods and a brickwork or a concrete lining is inserted which at the base carries a cast iron anchor ring which is connected to two concentric rings of long rods, 4 in. square and 1½–2 in. diam respectively, the inner or guide ring passing down the face of the brickwork and the outer ring through the brickwork (Fig. 183). The two rings of bolts are connected at the surface to a strong pressure ring designed for the loading required which may amount to 2,000 tons to force down tubbing fitted with a cutting shoe about ¾ in. wider than the overall diameter of the tubbing to give clearance. The pressure on the tubbing is exerted by some twelve hydraulic jacks, supplied from a hydraulic accumulator, operating between the top of the tubbing and the pressure ring, special rings of low height being inserted at the top of the tubbing to accommodate this to the stroke of the jacks. The first few feet of the descent of the tubbing generally takes place under its own weight until skin friction becomes too great when the

jacks are brought into play, successive rings of tubbing being added as it descends.

Where it is not possible to insert brickwork or concrete near the surface to take the reaction of the hydraulic jacks, the anchor ring, *r*, and bolts, *a* and *z*, may be carried down by a brickwork cylinder fitted with a cutting shoe which descends by its own weight as far as possible (Fig. 184). The reaction of the hydraulic jacks is taken by the weight and the skin friction of this cylinder. German tubbing, *t*,

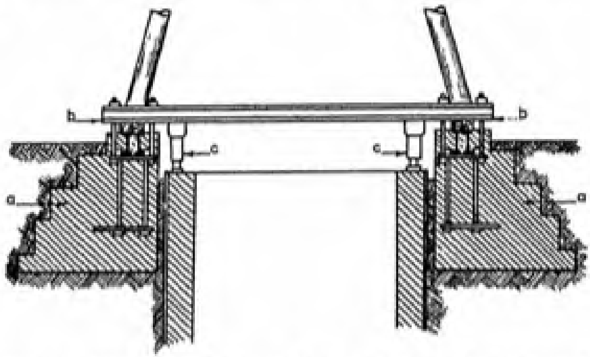


FIG. 183. DROP SHAFT AND PRESSURE RING IN STRONG GROUND AT SURFACE
(*a*) Brickwork or concrete; (*b*) Pressure ring; (*c*) Hydraulic jacks.

fitted with a cutting shoe is placed within the brickwork cylinder and the pressure ring, *d*, designed to withstand a pressure of 2,000–3,000 tons, is attached to the rings of bolts, *s* and *z*, and the hydraulic jacks, *p*, are then placed between the pressure ring and the top of the tubbing.

In these drop shaft methods water is often allowed to fill the shaft in order to prevent subsidence being caused by water pumped from the shaft conveying with it fine material, and debris is excavated by the use of clam-shell and orange-peel grabs, depending upon the particle size of the material which, in running sand, is often extremely small. When stable strata is reached the drop shaft is sealed into it with cement (Fig. 185).

3. CAISSON SINKING

In this system, which is particularly applicable to sinking in wet running sand containing boulders which renders it necessary to have men working at the bottom of the shaft, an airtight deck, *a* (Fig. 186), is formed 7 ft to 8 ft above the cutting shoe of a drop shaft, *m*. The deck is generally of reinforced concrete and must be strong

enough to withstand the maximum air pressure required to keep back the water and running sand at the shaft-bottom provided this does not exceed 50 lb/in.^{2}, corresponding to a head of 115 ft of water, which is about the limiting pressure in which men can work. The airtight deck is connected to the surface by a steel tube, *r*, from 3 ft to 5 ft in diameter in lengths of 10 ft to 15 ft bolted together, with rubber joint rings. The walls of the tube are $\frac{3}{8}$ in. or more in thickness and the tube is provided with ladder rungs.

The tube is connected at the surface to an airlock with two doors to prevent the escape of compressed air. When men or the sinking hoppet are required to enter the working chamber the outer door is opened with the inner door closed. The men or the hoppet enter the airlock and the outer door is closed. Compressed air is then admitted until the pressure in the lock is equal to that in the working chamber. The inner door is then opened and the men travel down the ladder or the hoppet is lowered into the working chamber. When men leave the chamber or the full hoppet is to be raised the operations are reversed. To combat the extra buoyancy, due to the uplift of the compressed air, the drop shaft must either be heavier or extra weight in the form of steel rails must be added to it.

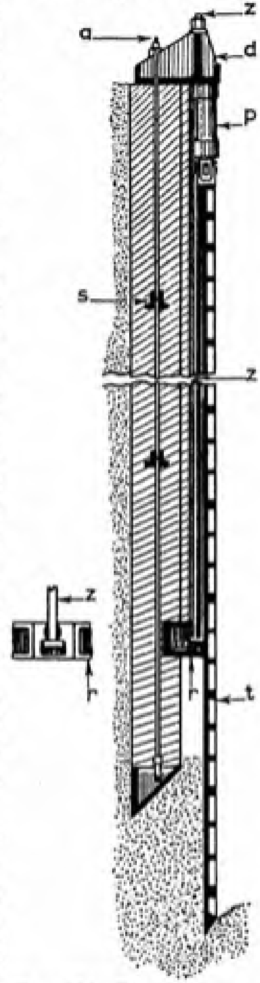


FIG. 184. DROP SHAFT IN WEAK GROUND WITH PRESSURE RING, ANCHOR RING, HYDRAULIC JACKS AND TUBBING (HERBST)

There are several forms of airlock. In the Mattsen lock the upper door is of the revolving type and the rope passes through a stuffing box in the top of the airlock casing. The hoppet is detached from the rope and removed from the lock, an empty hoppet then being attached to the hoisting rope. In the Moran lock the upper door is in two halves which close round the rope or a single door is used with a stuffing box for the rope. This lock enables the hoppet to be lifted out of the lock by the rope. A type of lock which has been used on the Continent is shown in Fig. 186 in which the hoist, *h*, is enclosed in the lock, *K*, which has

two sets of debris locks, s_1 and s_2, fitted with pairs of doors, d_1 and d_2 and d_3 and d_4, which are filled alternately and deliver to a deck, *b*, from which the debris is hoisted by an external derrick. A separate airlock for men and materials, *V*, is fitted with two side doors, t_1 and t_2.

The compressed air is supplied from a low-pressure compressor through a duplicate 4 in. main. The higher the air pressure required the shorter the period men can work in the chamber amounting by law in the U.S.A. to two shifts of only half an hour in twenty hours,

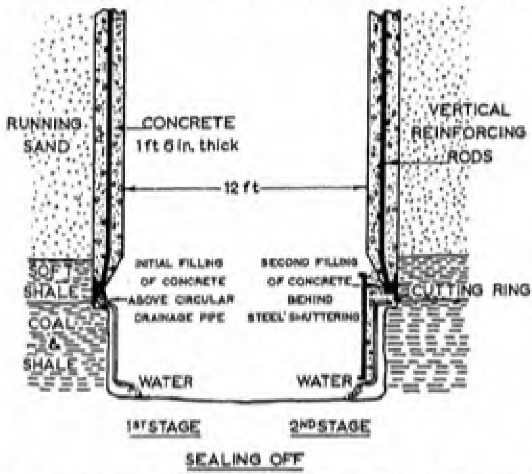


FIG. 185. SECTION OF CUTTING RING IN DROP SHAFT METHOD SHOWING SEALING

with at least six hours between shifts, when the air pressure is 48 to 50 lb/in.[2] which makes the cost of caisson sinking very high. Care must be taken that men enter a decompression chamber in which the pressure is gradually reduced to atmospheric pressure. Owing to saturation of the blood with nitrogen at the high pressure, bubbles of nitrogen separate out from the blood and block the arteries and veins if the pressure is reduced too quickly. This gives rise to caisson sickness which is characterized by dizziness and fainting and by pains in the joints, where the bubbles tend to collect and coalesce, and in the stomach giving rise to a characteristic bending posture which has given the illness the slang name of the "bends." Caisson workers carry an indication of their calling; if they are affected away from their place of work should be taken there and gradually subjected to greater pressure which should then very gradually be reduced.

Caisson work is extensively used for foundation work in civil engineering projects and its application to shaft sinking is a relatively minor one. Helium and oxygen mixtures, in place of air, is used in caisson work and in diving. Helium is less soluble in blood and diffuses more easily than nitrogen so that greater pressures and shorter decompression periods are permissible when such mixtures are used.

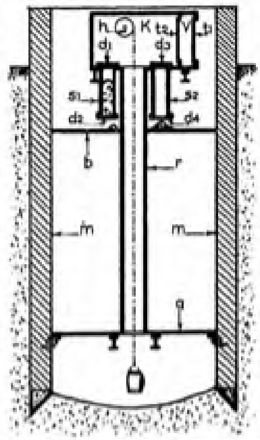


FIG. 186. CAISSON SINKING (HEISE HERBST)

Two colliery shafts 20 ft and 16 ft in diameter were sunk by the caisson method through 140 ft of sands and gravel, 111 ft of which was water-bearing, at Terre Haute, Ind., U.S.A. by the Dravo Contracting Co. in 1923. The caissons and decks were of reinforced concrete, the walls being 4 ft in thickness. The air pressure attained 51 lb/in.^{2} and great difficulty was experienced in landing the caissons plumb. The new shaft at Point of Ayr Colliery in North Wales was in 1952 sunk by the caisson method.

METHODS OF BORING OUT SHAFTS

Small-diameter shafts and staple shafts up to 6 ft in diameter are, as has already been noted, bored out by the calyx system in Germany and in the U.S.A. but the practice of boring out shafts is of long standing, dating back to 1876 in this country. It was used where the ground, though heavily water-bearing, was sufficiently strong to stand, generally filled with water, long enough for the shaft to penetrate the water-bearing strata when the permanent lining, generally German tubbing, was inserted.

These methods, owing to the size and weight of the tools required, were limited in the diameter of shaft which could be bored and have been superseded by freezing and cementation methods. However, it is by no means certain that they may not at any time be revived in view of the recent steep rise in the cost of manual labour, and in fact, one of these systems, improved in detail, the Honigmann, was adopted to sink the new Emma No. 4 shaft for the Dutch State Mines in 1949, so that a short description of these methods is not out of place.

Kind-Chaudron

The oldest system is the Kind-Chaudron which has been used to sink successfully some eighty shafts. Operations commence with the

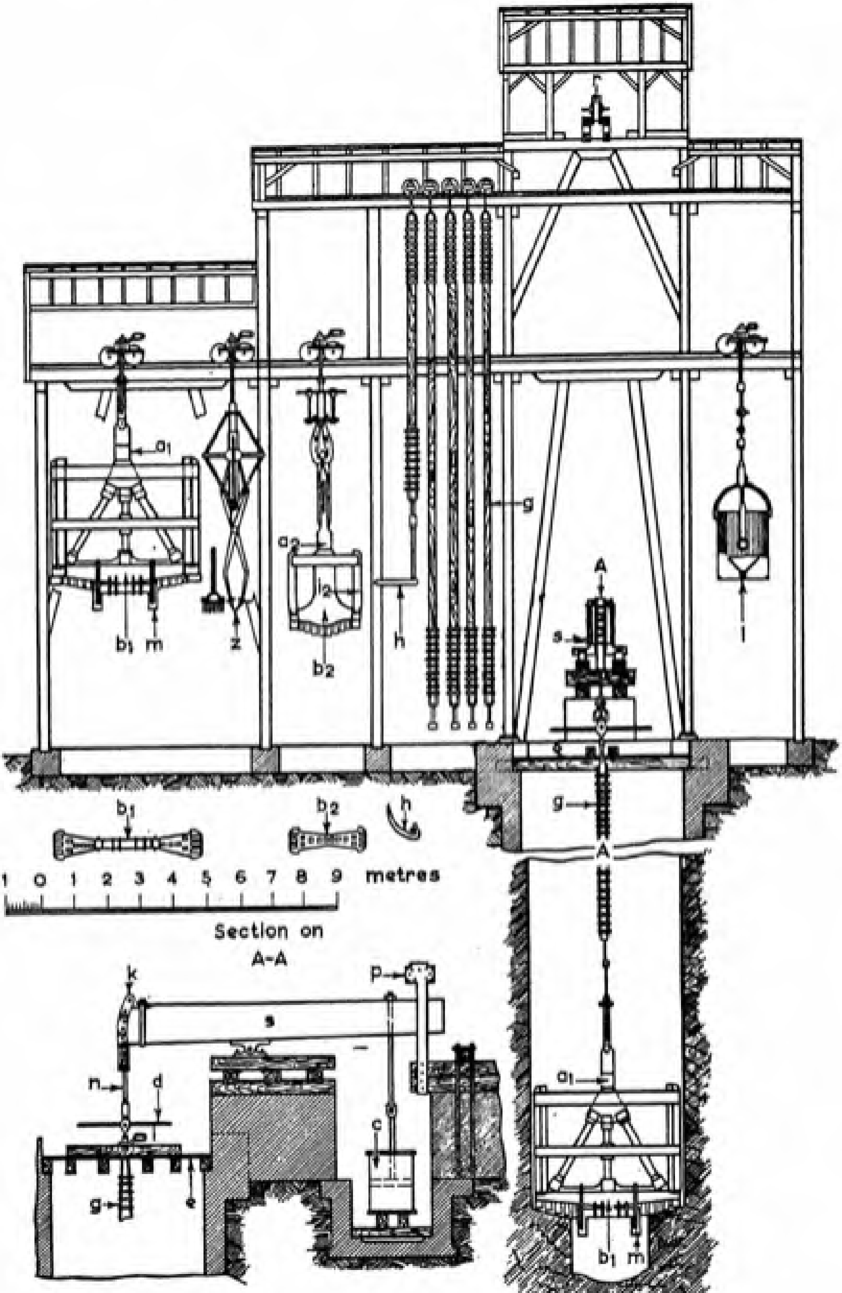


FIG. 187. KIND-CHAUDRON METHOD OF SINKING (HEISE HERBST)

erection of a baraque or special type of derrick (Fig. 187), to house the boring tools or trepans, a_1 and a_2, the pitch-pine rods, *g*, fishing tools, *h* and *z*, the sludger, *l*, the walking beam, *s*, and the cylinder, *c*.

A small-diameter shaft is first bored 4 ft to 10 ft in diameter using the small trepan, a_2, weighing 10 tons, equipped with chilled-steel cutters arranged to cut the shaft bottom in the form of a cone, from the base of which the cuttings are lifted by the sludger, *l*. The rods are reciprocated by the walking beam, *s*, and turned by the crosshead, *d*, the trepan being connected to the rods through the Kind's type free-fall apparatus shown. The water-bearing strata may be penetrated before enlargement begins or enlargement may follow the

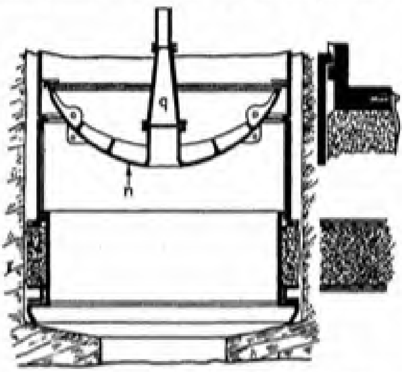


FIG. 188. MOSS-BOX USED WITH KIND-CHAUDRON METHOD OF SINKING

boring of the small diameter shaft by 30 ft or so. The enlargement is carried out by means of the large trepan a_1, weighing 25 tons, which is fitted with guides, *m*, projecting into the small-diameter shaft to maintain verticality. The cuttings fall into a hoppet in the small shaft. When the shaft has been bored out to the full diameter to the impervious strata, tubbing is lowered with a moss-box beneath (Fig. 188), fitted with a false-bottom, *n*, provided with an equilibrium tube, *q*, to enable the tubbing to be lowered gradually into place by manipulation of a valve which regulates the passage of water above the false-bottom. The moss-box is relied upon to form a water-tight seal at the bottom of the water-bearing strata. It consists of two telescopic sections of tubbing with the moss, confined by a hemp mesh, between them which is compressed when the weight of the tubbing above comes upon it. Concrete is then placed by drop-bottom containers between the tubbing and the side of the shaft. The water is then pumped out of the shaft. The false-bottom and the cutting shoe is removed, or a special curb placed beneath it. Sinking

then continues in the normal manner. Sometimes the moss-box is omitted, the seal being completed by using concrete, the tubbing landing upon a prepared bed. The Marsden and the Dover collieries were sunk by this method and sinking to a depth of 450 yd has been accomplished on the Continent.

The Honigmann System

This system is illustrated in Figs. 189, 190 and 191. It consists of a rotary borer, *s*, driven by a hollow stem, *h*, and lowered by the hoisting rope attached to the D link. Compressed-air lift or Mammoth pump, supplied by pipe, *r*, removes the cuttings from the shaft which are delivered to a settling pond, the clayey water being returned to the shaft at *o*.

The system is used in water-bearing weak strata, a mud-flush system being adopted to support the unlined sides of the shaft during sinking. By inserting tubbing above the water level an artificial head is created in the shaft and this is increased by adding clay which increases the specific gravity of the liquid in the shaft to as much as 1·2 and also coats and supports the sides of the shaft. When sinking through clay about 15 per cent of clay is added to the water, in sand 20 per cent and in gravel 35 per cent. The boring tool is rotated through a train of gears, *f*, *g*, *p*, and connection to the settling pond is through the swivel joint, *l*, and the flexible hose, *n*, to the launder, *m*.

When the impervious strata is reached the boring tool is withdrawn and the shaft is enlarged by heavier tools (Figs. 190 and 191), the cuttings falling into the smaller shaft and being removed by the air lift up the hollow shaft, *h*.

The number of times the shaft is reamed out depends upon the ultimate diameter of the shaft required and the hardness of the strata penetrated.

In sinking the Emma No. 4 shaft, a foreshaft was first excavated to the ground water level and a pilot hole 27½ in. diam was bored and the shaft was reamed out in three consecutive operations until the final diameter of 19·2 ft was obtained, using the hole previously drilled to guide the reamer. In softer ground drag bits were used (Fig. 190), in the harder rollers were used fitted with steel picks (Fig. 191), each roller carrying 1,000 picks of high-tensile steel, tungsten carbide tipping not proving successful. The speed of the largest borer was 1·8 rev/min and over 60 ft^3/min of material was removed.

The mud flush circulated amounted to 180 ft^3/min and bits were replaced after a period averaging sixty hours. When the water-bearing strata has been penetrated German tubbing is lowered and sealed in a similar manner to the Kind-Chaudron method.

At Emma Colliery when the impervious strata was reached at a depth of 246 yd the shaft was lined with two concentric rings of Gusto welded steel tubbing 17·4 and 14·75 ft in diameter respectively

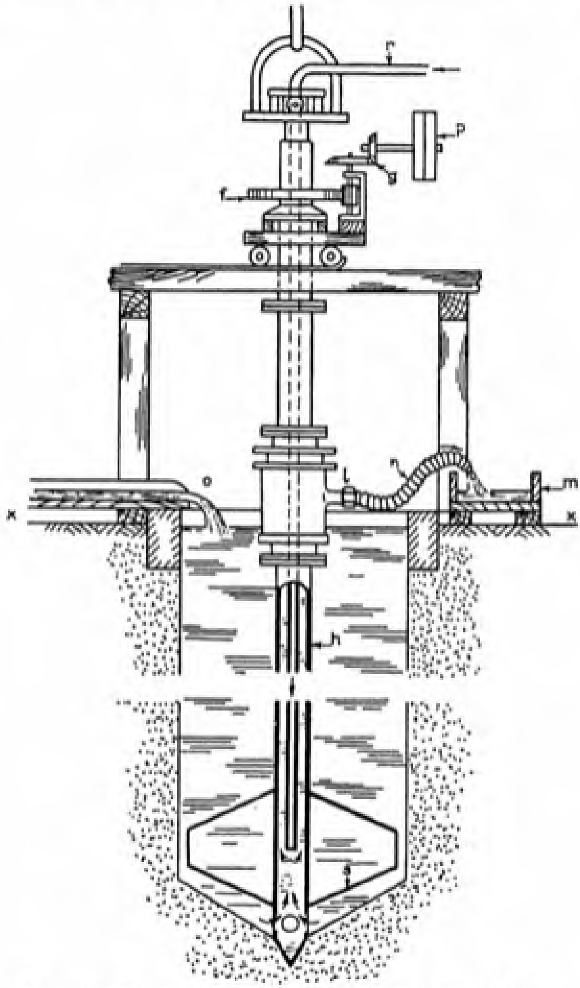


FIG. 189. HONIGMANN METHOD OF BORING OUT A SHAFT

with concrete between the shells and between the outer shell and the shaft wall. The tubbing was fabricated from steel sheets $\frac{9}{32}$ in. in thickness at the top and $\frac{41}{64}$ in. at the bottom of the water-bearing strata, 6 ft 6 in. wide and of length equal to half the circumference of

the inner or the outer shell. These were cut accurately to size, the edges bevelled and the plates bent to the correct curvature by rolls. They were then welded together to form rings 13 ft 2 in. in height, steel strips being welded to the plates to increase the bond between the plates and the concrete. A concrete plug was formed in the first section of the lining and accurately positioned by roller guides and hydraulic jacks and lowered into the shaft. Successive lengths of tubbing were then welded to it with concrete wedges between the

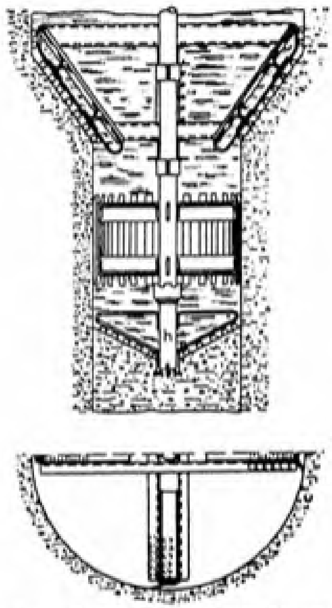


FIG. 190. HONIGMANN BORING TOOL USING DRAG BITS FOR SOFTER STRATA (KNOX)

shells and this inner annulus was then filled with concrete. When a depth was reached at which the lining floated on the mud suspension, water ballast was pumped into the inner cylinder, the mud suspension being kept in circulation by four air lifts placed between the outer shell and the shaft wall. The lining was landed into a plug of cement grout injected through the mud circulation pipes which were then used to grout between the shaft wall and the lining.

In addition to the Emma shaft, the Hendrick No. 3 shaft, 17 ft finished diameter, was sunk by this method through 220 yd of gravel, sand, quicksands and clay and at Arsbeck a shaft 19 ft 8 in. was sunk to a depth of 458 yd through similar strata.

The cost of sinking in 1932 varied from £100 per yd at 100 yd to £500 at 500 yd, the rate of sinking being 18 and 9 yd per month respectively.

The Pattberg system is similar but employs a sack debris removal system and does not incorporate the mud flush system for the support of the unlined shaft. It is generally employed in conjunction with a drop shaft system, as many as four linings, one within the other, being required in water-bearing strata 500 ft in thickness.

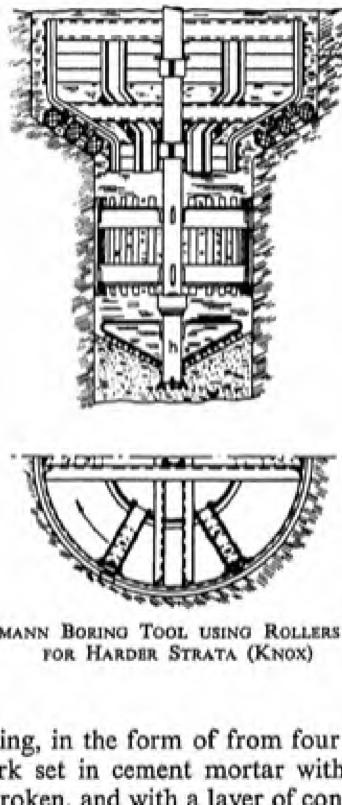


FIG. 191. HONIGMANN BORING TOOL USING ROLLERS WITH STEEL PICKS FOR HARDER STRATA (KNOX)

Tubbing

Although coffering, in the form of from four to eight concentric layers of brickwork set in cement mortar with the joint between individual layers broken, and with a layer of concrete between pairs of layers, may be used at shallow depth to hold back water at a low head, a considerably greater shaft excavation is required to accommodate the thick brickwork lining.

Coffering with a bitumen seal was used at Willem Sophia No. 3 shaft in Holland, 14 ft 9 in. in diameter, which was sunk by the freezing process. The shaft was lined through the frozen ground in two stages. The first consisted of one foot of brickwork which

formed the shuttering for a further foot of concrete to the shaft wall (Fig. 192), the concrete being put in as dry as possible and vibrated to avoid cavities. When this first lining was completed the final lining of three courses, headers of brickwork, 2 ft in thickness, was inserted with ½ in. thick layer of bitumen between the linings to form

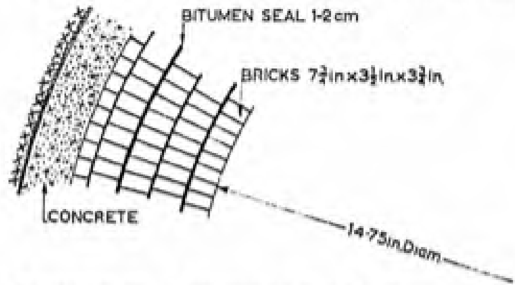


FIG. 192. ARRANGEMENT OF BRICKWORK AND CONCRETE LINING SHOWING POSITION OF BITUMEN SEAL (N.C.B. BULLETIN)

a watertight seal. To thaw out the brickwork before the application of the bitumen 100 infra-red radiation lamps aggregating 25 kW were installed on the bricking scaffold. Ease of repair was the reason for using brickwork for the outer lining.

For greater depths cast iron tubbing has been used since 1796 to hold back water when it was first used by John Buddle. It is, however, an increasingly expensive method of lining and is being

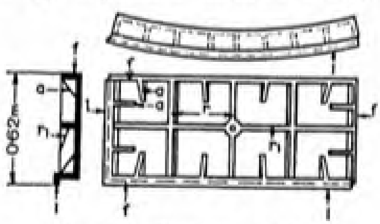


FIG. 193. ENGLISH TUBBING

replaced by concrete and reinforced concrete even in shafts sunk by the freezing system, although trouble due to freezing, affecting the setting of the concrete, may be experienced. Tubbing is, however, still commonly employed in the freezing and boring systems of sinking.

There are two main types of tubbing, the English with flanges external to the shaft (Fig. 193), which are in tension and therefore less strong than German tubbing with flanges internal to the shaft which are in compression and therefore stronger (Fig. 194), so that

German tubbing is lighter than English for the same head. A further difference lies in the fact that English tubbing is cast and depends for its watertightness on pine sheeting between the vertical and the

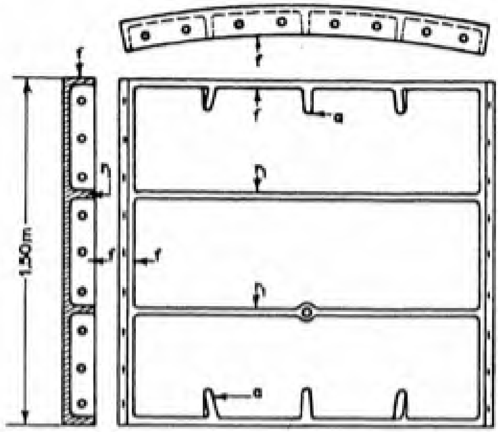


FIG. 194. GERMAN TUBBING

horizontal joints into which wooden wedges are driven until no more can be inserted. German tubbing on the other hand is machined and has lead sheeting in the joints (Fig. 195), and the segments are bolted

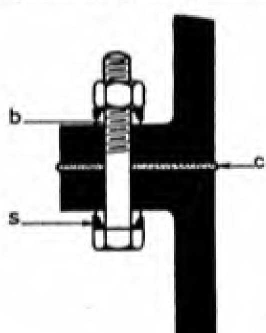


FIG. 195. JOINT OF GERMAN TUBBING

together by accurately fitting bolts (Fig. 171). English tubbing is more flexible by virtue of the wood sheeting in the joints and therefore less likely to suffer damage if the shaft is subjected to stress due to subsidence. It offers less resistance to the ventilation as the lining is smooth and accommodates itself better to seasonal temperature

fluctuations. On the other hand German tubbing, which can be underhung, built up, caulked on the surface and then lowered into the shaft, is quicker to erect and can be designed for higher heads.

ENGLISH TUBBING

This is cast to suit the radius of the shaft in segments, generally eight to twelve to the complete ring. Each segment, 2 ft 6 in. to

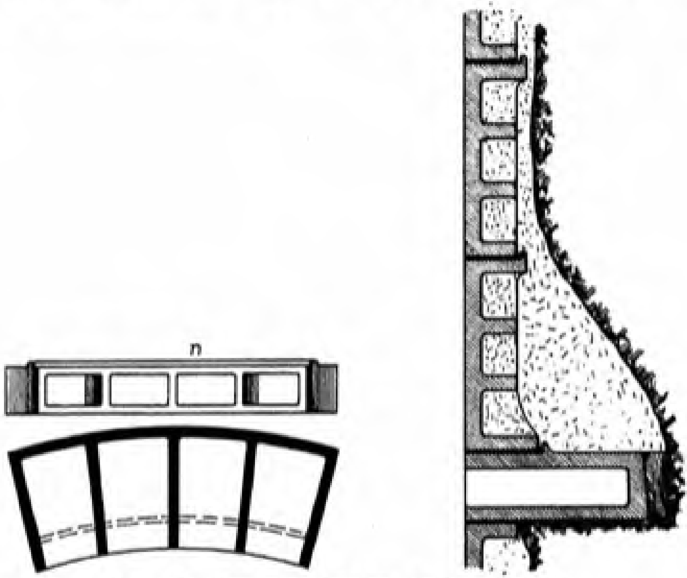


FIG. 196. WEDGING CURB FOR ENGLISH TUBBING

3 ft deep and 4 ft to 5 ft in length, is smooth on the inside but has strong external flanges, f (Fig. 193), lipped to fit adjacent segments and strengthened by ribs, r and r_1, and angles, a, with a hole in the centre for handling and to let air and water out from behind the tubbing, being closed finally by a wooden or an iron plug. The bottom ring of tubbing resting on the curb, and known as the foundation ring, is often provided with a wider bottom flange.

When erecting tubbing a wedging curb bed is prepared in as strong and impervious strata as is available. This is carefully levelled by picks and wedges and without the use of explosives which would cause shattering and then covered with pine sheeting $\frac{1}{2}$ in. to $\frac{3}{4}$ in. in thickness and tarred flannel. The curb consisting of a hollow ring (Fig. 196), in section and segments with a lip, n, to hold the bottom ring of tubbing in place is next placed on the bed. Pine sheeting is

placed between the curb segments and the centre-line and radius rod are used to position the curb accurately, a straight edge and level being used to set it accurately horizontal. Each curb segment is then spragged to the side of the shaft and wedging up commenced. Glutting blocks of dry pine 6 in. by 6 in. by $2\frac{1}{2}$ in. are driven down between the curb and the rock all round. Pine followed by oak wedges are then driven in until no more can be inserted when a steel chisel is used to make room for further wedges. The setting of the curb is then rechecked for alignment and level. The bottom or foundation ring of tubbing is then erected on the curb with $\frac{1}{2}$ in. thick pine sheeting between the horizontal and $\frac{3}{8}$ in. sheeting between vertical joints, wedges driven behind the segments and the sides to position them and the ring is then checked; if correct the space behind is packed with concrete. The operation is continued, the joint between adjacent segments being broken by half or quarter of the width of a segment. An escape path is left behind the tubbing and through any intermediate curb ring, via a relief valve, and at the top to allow air or gas to escape which otherwise when compressed might force out a segment of tubbing. Wedging of the pine sheeting now proceeds from the top to the bottom of the tubbing and then, in the reverse direction, using steel chisels to split the sheeting to allow further wedges to be driven in until the chisel can no longer be inserted.

German Tubbing

The segments of German tubbing are generally deeper than English tubbing, 2 ft $5\frac{1}{2}$ in. to 4 ft 11 in. ($\frac{3}{4}$ to $1\frac{1}{2}$ metres), and 4 ft 11 in. to 6 ft $6\frac{3}{4}$ in. ($1\frac{1}{2}$ to 2 m) in width. The flanges, f (Fig. 194), are bored and machined after casting and are strengthened by angles, a, and ribs, r_1, reinforce the segments, the external circumference being smooth or corrugated to get a firmer grip on the concrete backing.

When installing tubbing a curb is used in segments which are bolted together with strips of sheet lead from $\frac{1}{16}$ in. to $\frac{1}{8}$ in. thick between segments. Concrete or brickwork is used at times to form a satisfactory curb bed and in weak ground the curb is erected on two rings of tubbing u_1 and u_2 (Fig. 197), on wooden blocks and the curb embedded in concrete, B. The next three rings are also backed by thick concrete, C. The curb may afterwards be filled solid with cement slurry. The tubbing is then erected on the curb with strips of lead sheeting between the horizontal and the vertical joints which project $\frac{1}{4}$ in. for caulking by a chisel or compressed air caulking tool, C (Fig. 195). Glutting blocks, p_1 (Fig. 198), are again placed

between the curb, *k*, and the shaft side, wedges being driven into the blocks. The bolts for connecting the tubbing segments are turned to give $\frac{1}{16}$ in. clearance and are provided with conical cast steel washers, *s* (Fig. 195), over lead washers, *b*, which when tightened up force the lead into the hole clearance. The tubbing is grouted behind with provision for water and air release. When closing the tubbing

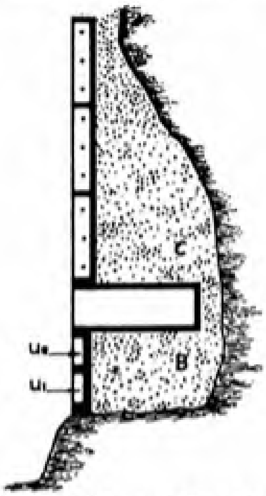


FIG. 197. WEDGING CURB FOR GERMAN TUBBING IN WEAK GROUND (HEISE HERBST)

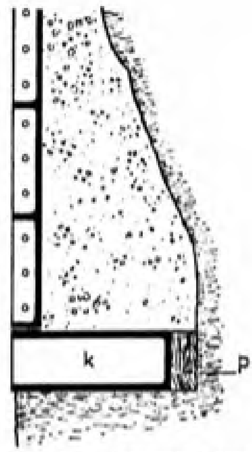


FIG. 198. WEDGING CURB FOR GERMAN TUBBING

against a wedging curb above, a shaft stuffing-box may be used consisting of two short telescopic rings, the outer ring being bolted to the wedging curb above and the inner forming the top ring of the length of tubbing below. Alternatively the top matching ring of tubbing may be wedged in position by the use of wooden wedges. This gives the tubbing flexibility to accommodate itself to shaft movement.

UNDERHUNG GERMAN TUBBING

Underhung or suspended tubbing has the advantage of dispensing with the temporary shaft lining as the tubbing is installed immediately the necessary ground has been removed for a ring of tubbing to be put in (Fig. 199). The anchor ring or curb, *k*, is put in in strong ground in the usual manner with glutting blocks, *p*, and well backed with rammed concrete. The segments of tubbing are lowered by chains from the hoisting rope which are replaced by hooks in the

shaft bottom. These lift the segment approximately into position, the lead sheeting is inserted and then two long bolts are used to draw the segment into position. These are later replaced by standard bolts. When two or three rings have been put in they are grouted behind through the holes, *e*, in the segments which point downwards, the funnel, *t*, being used and the bottom hole plugged. The grout is retained in position while setting by sheet iron segments, *a*, fitting closely to the side of the shaft which are bolted to the bottom flange of the tubbing. The grout, which is a mixture of one part cement to between two and four of sharp sand, sets in about two days after which the segments are removed.

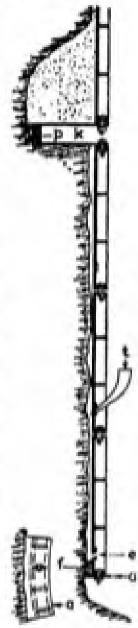


FIG. 199. UNDERHUNG GERMAN TUBBING (HEISE HERBST)

THICKNESS OF TUBBING

The maximum thickness of tubbing that has been used is $7\frac{1}{16}$ in. This was used at Limbourg Meuse and at other Campine and Ruhr sinkings. At deep sinkings double tubbing, though more expensive both in first cost and in cost of installation, has been adopted consisting of two rings of tubbing with concrete or reinforced concrete between, particularly where the freezing system has been adopted as at Beeringen. Corrugated tubbing has also been adopted to give greater flexibility to the lining to resist damage by subsidence.

There are a number of formulae used for calculating the thickness of tubbing required. They give slightly differing results and the thickness is often estimated empirically from the successful lining of previous shafts in similar conditions. The following are the formulae which have commonly been adopted. They are all based on the compressive strength of a thin cylinder with allowances for flaws, corrosion and deterioration and adopt a factor of safety between 5 and 10, 7 being often adopted.

(*a*) *Greenwell Formula*

$$T = 0{\cdot}03 + \frac{HD}{50{,}000}$$

where T is the required thickness of tubbing in *feet*,
H is the vertical depth in feet,
D is the diameter of the shaft in feet,
0·03 is an allowance for possible flaws or corrosion.

(*b*) *O'Donaghue Formula*

$$t = \frac{hdF}{2C} + A$$

where t is the required thickness of tubbing in *inches*,
h is the pressure of water in lb/in.^{2},
d is the diameter of the shaft in inches,
C is the crushing strength of cast iron in lb/in.^{2} which may be taken as 95,000,
F is the factor of safety adopted between 5 and 10,
A is the allowance for possible flaws and corrosion and may vary from $\frac{1}{4}$ in. to 1 in., averaging $\frac{1}{2}$ in.

(*c*) *Riemer Formula*

$$t = \frac{130}{H} + \frac{0{\cdot}43DH}{1{,}600}$$

where t is the thickness of tubbing required in *inches*,
D is the internal diameter of the shaft in feet,
H is the head of water in feet.

(*d*) *Denoël Formula*

$$t = R_1 - R = \left\{\sqrt{\frac{T}{T-2P}} - 1\right\}$$

where t is the thickness of tubbing required in *centimetres*,
R_1 and R external and internal diameters of lining in centimetres,
T is the safe stress of 1,000 kgm/cm^2, in cast iron,
P is the water pressure in kgm/cm^2.

This may be simplified to the approximate formula—

$$t = \frac{2PR}{2T - 3P}$$

The Freezing System

The freezing system of sinking has been used extensively on the Continent to penetrate water-bearing strata consisting of alluvium and running sand down to a depth of 2,000 ft, with a water pressure in running sand of 800 lb/in.^{2} It has also been used successfully at Londonderry Colliery near Seaham Harbour on the NE. Coast, in 1924–28 to sink the Vane and the Tempest shafts, 21 ft in diameter, through 487 ft of magnesian limestone with open gullets communicating with the sea and with running sand below, and at the No. 2

shaft 22 ft 2 in. in diameter at Calverton, near Nottingham, in 1948–49 to sink through 390 ft of heavily fissured and water-bearing Bunter sandstones, No. 1 shaft having been sunk by cementation. This sealed off the water from the fissures but the water contained in the porous strata had to be dealt with by pumping during sinking and exceeded 1,000 gal/min at times, giving a wet sinking.

In the conditions encountered on the NE. Coast, similar to those at Londonderry, various methods have been used at previous sinkings—ordinary sinking with pumps dealing with, exceptionally, over 10,000 gal/min, the Kind-Chaudron System and early applications of the freezing system.

The freezing method consists of forming in the water-bearing strata a solid block of frozen ground, estimated at Londonderry to extend 12 to 15 ft outside the excavated area of the shafts and 70 ft in diameter at Calverton, sufficiently strong to hold back the water at the depth required while the shaft is sunk in the frozen strata with consequently no water difficulties. The operation at Londonderry was complicated by the rise and fall in the shaft of the water, which was brackish, of 3 to 4 ft with the tide with a lag of four hours.

Boring

The frozen cylinder is produced by boring a ring of holes on a circle of radius greater than that of the shaft to be excavated, 32 holes on a circle of 30 ft diam at Londonderry where the diameter of the excavated area was 27 ft, and 25 holes on a circle of 33 ft diam at 4 ft intervals at Calverton. In both cases the boreholes were continued into the impervious strata below the water-bearing strata, at Londonderry 48 ft into the Coal Measures and at Calverton 22 ft into Permian Limestone, which contained water but in which it was proposed to adopt cementation. In both cases a hole was bored previously from which a forecast could be made of the measures to be taken during the freezing operations.

The boreholes were put down by the percussive system (Fig. 149), using a derrick running on concentric rails set in a floor of concrete. A heavy sinker bar 30 ft kn length was used to improve the verticality of the holes. They were surveyed at Londonderry by a Briggs Clinophone and at Calverton by a Dennis-Foraky Teleclinograph to ensure the deviation of holes would not produce a gap in the ice wall. At both sinkings an extra hole was put in where a hole had deviated but in the case of other holes the deviation was less than 1 per cent at Londonderry but rather more at Calverton.

At Londonderry the holes were $9\frac{7}{8}$ in. diam to a depth of 175 ft and were lined with $9\frac{1}{2}$ in. diam tubes, $8\frac{1}{4}$ in. diam with 8 in. tubes to

300 ft, $7\frac{1}{2}$ in. diam to 435 ft and the remainder $6\frac{1}{2}$ in. diam, the hole then being lined with 6 in. tubes throughout. The freezing tubes were then inserted, the outer tubes being 5 in. diam and sealed at the ends and the inner tubes 2 in. diam open at the ends, all joints being tested to 300 lb/in.^{2} to prevent leakage of brine which would interfere with freezing. At Calverton the outer freezing tubes varied from 3 in. to 6 in. diam and were $\frac{5}{16}$ in. thick, the inner open-ended tubes

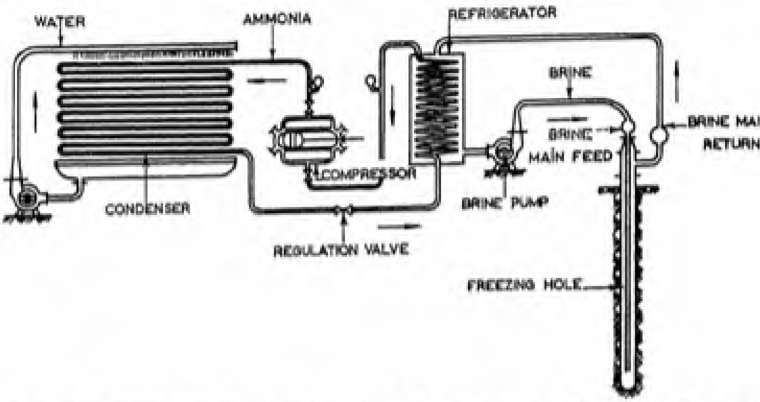


FIG. 200. BRINE AND AMMONIA CIRCUITS IN THE FREEZING METHOD OF SINKING

being $1\frac{1}{2}$ in. diam. The whole brine circulating system was tested to 400 lb/in.^{2}

FREEZING

The refrigerant used may be ammonia or carbon dioxide but the former is usually preferred since the CO_2 requires a higher vacuum although a smaller volume is necessary. As may be seen from Fig. 200, the freezing system is divided into two separate circuits—ammonia circuit and the brine circuit—and the whole comprises a heat exchange system.

In the first circuit ammonia gas is compressed to eight atmospheres (120 lb/in.^{2}), and passes to the top of the trickling condensers by which heat is extracted from the compressed ammonia and it becomes liquified. The water for the condensers is circulated by a group of pumps working in conjunction with a cooling tower. The liquid ammonia is then passed through a regulating valve to the brine coolers where it evaporates extracting its latent heat of evaporation from the brine and so cooling it. The ammonia gas then passes to the ammonia compressors where it is again compressed and delivered to the condensers, thus completing the ammonia circuit.

The brine, consisting of a solution of calcium chloride of density 1·25, is circulated in the second distinct circuit by the brine circulating pumps shown to a header connected to the inner freezing tubes down which the cooled brine flows and returns up the annulus between the inner and outer freezing tubes extracting heat from the

FIG. 201. CONNECTIONS TO BOREHOLES IN FORESHAFT OF A SINKING BY THE FREEZING METHOD

strata and returning to a second header which delivers to the top of the coolers, thus completing the brine circuit.

The plant at Londonderry had a refrigerating capacity of 540,000 frigories (negative calories) per hour at minus 20°C and consisted of one large and two smaller ammonia compressors, eight ammonia evaporators, four condensors and five double-acting brine pumps. At Calverton the plant consisted of three Haslem ammonia compressors each capable of 280,000 B.t.u., three evaporators, three condensors and two brine circulating pumps. The main intake and return headers are contained in a fore-shaft or circular duct 7 ft by 7 ft and of mean diameter 33 ft at the top of the shaft (Fig. 201).

There are two methods of forming the ice-wall. At Calverton the brine, circulating at an inlet temperature of — 4°F and a return brine temperature of + 6°F, formed ice round the individual freezing tubes which gradually increased in thickness until the cylinders

coalesced and formed a thin barrier of ice round the area to be excavated. This wall was then thickened until the whole of this area and a thick wall outside was frozen solid, any water trapped inside the block being forced up the trial core borehole, near the centre of the shaft, which had a perforated lining.

At Londonderry only two diametrically opposite boreholes were put into brine circulation at first until the next four holes were sufficiently reduced in temperature, and then the next four and so on until all the holes were in circulation. The ice-wall therefore gradually grew in four different directions and finally joined in two places only. Valves enabled the circulation to the individual holes to be controlled and reversed if required. Sinking was commenced before the final thickness of frozen strata was reached at the bottom of the shaft. The brackish water and the rise of the tide required care to be taken with eutectic mixtures of salt and water which are difficult to freeze above the eutectic temperature of $-23°C$ when the mixture contains 23·6 per cent NaCl. Above this temperature ice or salt separates out from solution and the eutectic mixture freezes as a rather weak mass at $-23°C$, (Fig. 202).

SINKING

At Londonderry, after freezing, the sinking proceeded at a rate of 7 ft per day. Low-freezing explosives were employed. At Calverton the shaft was excavated to a depth of 52 ft, 8 ft above the water table, by means of a crane. The lining of this portion was of concrete and incorporated the fan-drift connection, headgear foundations and the shaft block. Below this was at first a soft core of unfrozen sandstone, 18 ft in diameter, but at a depth of 64 yd this had disappeared and below the block of frozen sandstone was 70 ft in diameter. Trouble was experienced from freezing-up of pneumatic tools and freezing in of drill steels. This was obviated by pouring brine at $+5°F$ into the holes. To warm the air for the men and to enable the 9 in. concrete backing behind the tubbing to set, three 15 kw factory heaters, each incorporating a slow-running fan, were suspended in the shaft from the surface and raised the shaft ambient temperature from 22 to 38°F.

TUBBING

In the water-bearing strata tubbing was used as a lining in both cases. At Londonderry the first 70 ft to the water-level was lined with 18 in. of brickwork and below this by English tubbing to a depth of 600 ft in rings 2 ft in height and 16 segments to the ring. For the first 40 ft the tubbing was $\frac{7}{8}$ in. thick and increased in thickness

by $\frac{1}{8}$ in. for every succeeding 40 ft, reaching a final thickness of $2\frac{3}{8}$ in. Five curbs were inserted and the space between the tubbing and the shaft sides was filled with quick-setting cement, 60 yd of shaft being sunk and then tubbing inserted at one time. The water pressure at

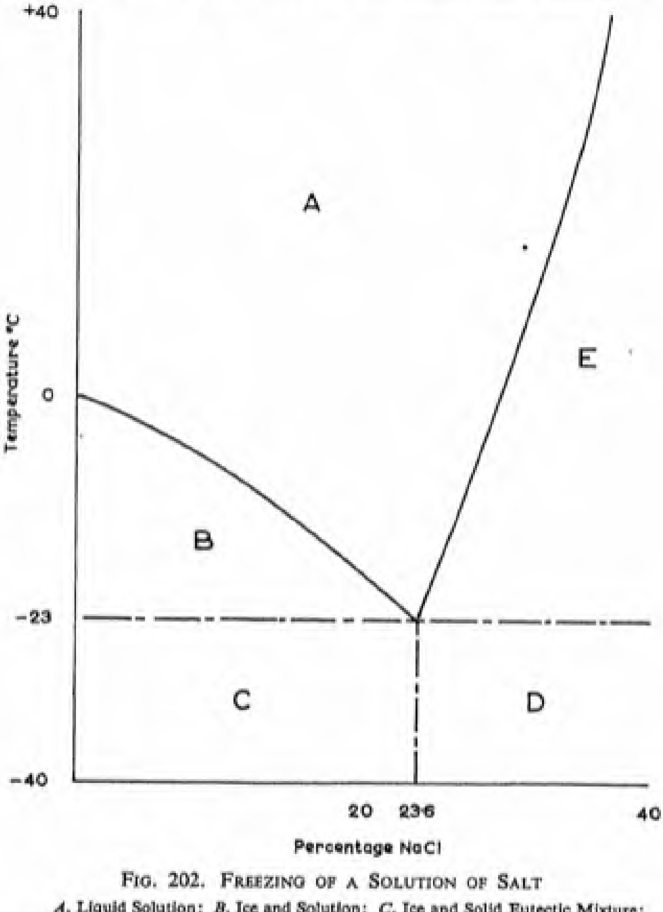


FIG. 202. FREEZING OF A SOLUTION OF SALT

A, Liquid Solution; *B*, Ice and Solution; *C*, Ice and Solid Eutectic Mixture; *D*, Salt and Solid Eutectic Mixture; *E*, Salt and Solution.

the base of the tubbing is 175 lb/in.^{2}. The total sinking time (exclusive of freezing operations) to a depth of 705 yd in the Coal Measures was twenty-two months.

At Calverton, German tubbing was used after the first 105 ft which was lined with 20 in. of concrete. The tubbing was inserted in four lengths of 46 ft, 100 ft, 80 ft and 60 ft respectively; the corresponding

thicknesses being $1\frac{1}{4}$ in., $1\frac{1}{2}$ in., $1\frac{3}{4}$ in. and 2 in. Below the tubbing the lining is of concrete 16 in. in thickness. The tubbing and the concrete are provided with recesses to carry the cross girders supporting the fixed guides used with the skip winding equipment installed.

THAWING

Previously shafts were thawed after freezing by passing steam down the freezing tubes, by circulating hot brine or by filling the shaft with water. The first two methods gave rise to trouble due to unequal thawing leading to breakage of pipes and cracking of tubbing in extreme cases. The last did not give access to the tubbing for caulking. At Londonderry arrangements were made to thaw each tube from the bottom upwards gradually so that the tubbing is subjected to a gradually increasing pressure as the ice-wall thaws upwards. Sinking into the Coal Measures continued as thawing proceeded. The same course was adopted at Calverton.

Cementation

When the make of water exceeds 500 gal/min and where the ground is not porous and does not contain open fissures, which on the NE. Coast may communicate with the sea, the cementation system may be adopted. The pressure required to reverse the flow of water gives an indication of the size of the fissures which will be encountered and the amount of cement required to seal them off. A pilot hole in the centre of the shaft in advance of the sinking will indicate the quantity of water that may be encountered.

Three possible methods of applying cementation are available. Holes may be drilled from the surface outside the shaft area and cement grout forced in at high pressure to seal off the fissures. Alternatively, the holes may be drilled from below the water table inside the diameter of the shaft in a vertical direction, the whole of the water-bearing ground being cemented from one set of holes. The method most commonly adopted, however, is to bore vertical or more often inclined holes from a number of levels in the shaft successively and cement off and sink in a corresponding number of stages.

In no case is an attempt made to seal the water off completely by cementation in the first stage. The make of water is reduced to an amount that can be dealt with easily by the pumps in the shaft and the complete seal is obtained by cementing behind the reinforced concrete shaft lining.

This method of boring and sinking in stages generally results in

economy in the use of cement and less trouble in sealing off the residual water behind the lining and is therefore generally adopted. The arrangement of the holes must be such that all fissures are intersected. The arrangements are shown in Fig. 203, in which a hole is placed every 2 ft 6 in. on the circumference of a circle approximately that of the finished shaft. These holes are bored off the vertical radially by an amount which throws them on a circle with a radius 10 ft greater than that of the shaft at a depth of 80–90 ft, which is the normal length of each stage. They are also inclined from the vertical tangentially so that with this radial and tangential "spin"

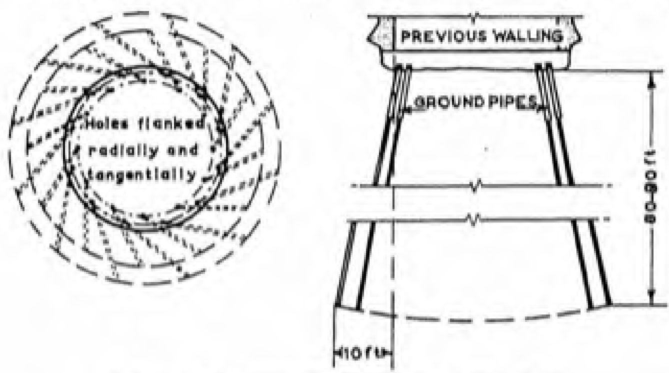


FIG. 203. POSITION OF HOLES FOR CEMENTATION

imparted to the holes all fissures are certain to be crossed by at least one hole. The rods used for drilling the depths required of 80–90 ft are plain hollow rods fitted with jack-bits screwed to the end, $1\frac{7}{8}$ in. diam, down which water flows in a continuous flush to remove the borings as they are produced. Normal machines are adopted for drilling the holes similar to those employed for the drilling of shot-holes.

In order to supply the requisite pressure to the grout to enable it to penetrate fissures against water pressure, an ordinary double-acting ram pump, 9 in. diam at the steam or compressed-air end and 2 in. diam at the water end, is used thus giving a pressure ratio of approximately 20–1. The pump valves are of the ball type which give minimum trouble when pumping cement milk.

GROUND PIPES

The drilling of the holes takes place through ground or stand-pipes to resist the pressure of the cement in the holes and prevent blow-backs. A hole 3 in. in diameter is bored to a depth of about 6 ft. It is then continued for a further 9 ft at a reduced diameter of $2\frac{3}{8}$ in.

which is the external diameter of a 2 in. pipe. A pipe of this diameter screwed at its outer end is then inserted to the full depth of the hole and is then injected, the cement milk finally returning between the pipe and the side of the hole. The cement is allowed to harden for twenty-four hours when the pipe is firmly fixed in the ground and should be capable of resisting any pressure put on the hole. This is tested by boring out the cement from the pipe to its full depth and pumping in clean water at the requisite pressure without leakage taking place round the pipe. A valve is now screwed to the pipe end and boring takes place through this valve, water flushing being adopted to clear the borings. If the return water disappears or decreases in quantity it is evident that a fissure, probably water-bearing, has been met. Similarly if the amount of water returning up the pipe increases in quantity this is also proof that a water-bearing fissure has been encountered. Boring is stopped and the hole is injected. After the cement milk has set the hole is re-bored to the same depth and the treatment of the fissure tested, by pumping in clear water under pressure in the same manner as that in which the stand-pipe was tested. If leakage occurs another injection is given and if this is successful boring is continued.

If it were possible to ensure that fissures in water-bearing ground were clean cementation would be a comparatively easy operation but all fissures generally contain sediment or clay which tends to impede the flow of water and a small diameter borehole can occasionally pass through a dirty fissure without indicating the presence of any water. It is usual, therefore, to adopt the stage method of working. The boreholes are divided into two groups, odd and even numbered holes. Even numbered holes are drilled first and are injected at intervals of about 10 ft. As far as possible boreholes are kept at the same depth, all injections in one stage being completed before the drilling of the next stage begins. Odd numbered boreholes follow about two stages behind.

From the cement consumption and the injection pressures required experience teaches whether results are satisfactory; if doubt exists extra boreholes are put down, an extra day spent on cementation being preferred to the handling of extra water and the possibility, in extreme cases, of flooding the shaft. Sinking stops short of the bottom of the cementation length by a distance sufficient to get in the stand-pipes for the next cementation length.

Cementation has recently been used to sink rectangular shafts in the Far West Rand where the gold reefs are overlain by 1,300–4,000 ft of dolomite. The upper parts of the dolomite often contain decomposed widely fissured bands filled with detritus of manganese dioxide

or colloidal clay. In these zones cement consumption reaches 50 ton/ft of sinking and averages 19 ton. The rate of advance achieved was 55 ft per month, a reinforced concrete lining 1 ft 6 in. to 2 ft in thickness being inserted. In normal dolomite consumption of cement was only 13 cwt/ft with a monthly average of 166 ft advance.

Cementation in Porous Ground

Porous rocks which contain water in substantial quantity in the pores of the rocks as well as in the fissures and joints—Triassic sandstones and in particular the Bunter series—require cementation to be supplemented by silicatization. This consists of alternating injections of so-called "products," aqueous solutions of sodium silicate and aluminium sulphate, which react to form a gelatinous precipitate of aluminium silicate. This serves to reduce the porosity of the rock and also to lubricate the fissures, which, in soft friable sandstones commonly contain large quantities of fine sand.

Without silicatization it is extremely difficult to introduce cement at any pressure. As an illustration of the lubricating value of this precipitate it was found that in a particular case only 20 lb of cement could be injected before silicatization at a pressure of 1,000 lb/in.^{2}. After the injection of 80 gal of chemicals, over 20 tons of cement was injected into the same hole at a pressure less than 250 lb/in.^{2}.

In such porous ground this treatment requires to be very intensive and there are more than twice the number of holes used in ordinary fissured strata. Thus in a shaft 22 ft in diameter 40 boreholes for cementation and silicatization may be required as shown in Fig. 204. The whole of the water is never sealed off, the aim being to reduce it within the capacity of a 1,000 gal/min pump and this may represent a reduction of 85 per cent.

Shafts in which freezing has been attempted but has failed present a difficult proposition owing to the deviation of boreholes, as at Thorne Colliery, but such sinkings have been successfully completed by cementation.

Reinforced Concrete Lining

As the water is not completely sealed off by silicatization and cementation preparations for lining the shaft must be made while sinking proceeds. Backsheeting of corrugated sheets is placed all round the shaft about 3 in. from the ground as sinking proceeds. This consists of light angles and 20-gauge sheeting prefabricated in segments 4 ft high by 8 ft to 10 ft long arranged for rapid and easy assembly in the sinking. The backsheeting fulfils two functions—it keeps the water from the concrete while it is setting and ultimately

forms part of the reinforcement of the wall. The inner cylinder, which is later removed, consists of the usual falsework of plates in rings 2 ft 6 in. in height. The concrete lining is reinforced in the manner shown in Fig. 205. Arrangements must be made to support the weight of the concrete and to conduct the water clear of the base of

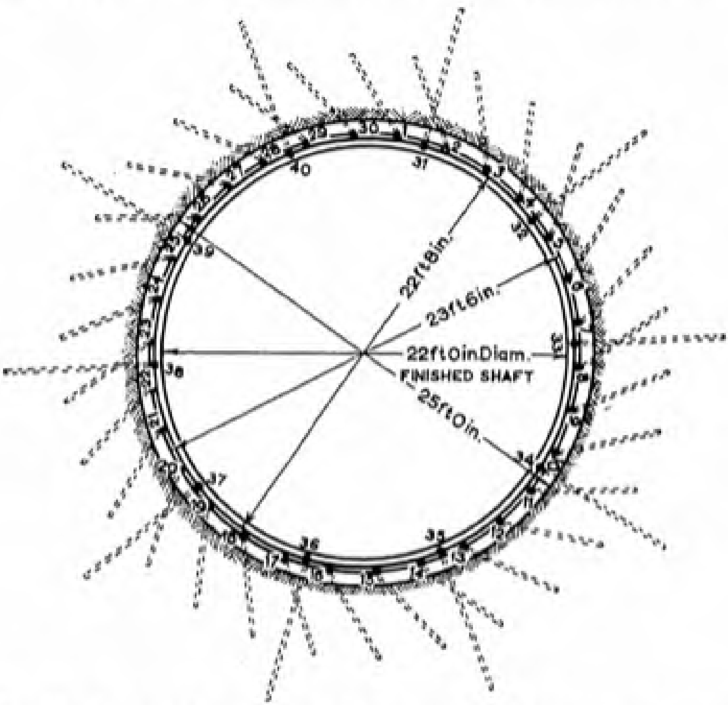


FIG. 204. PLAN OF CEMENTATION AND SILICATIZATION FOR POROUS SANDSTONE (ATHERTON)

the wall. A wedge of ground near the bottom of the length to be lined is excavated and a skeleton ring is placed opposite the wedge. Concrete placed in the wedge is continuous with that in the wall and the whole of the weight of the wall is temporarily transmitted to the ground at the base of the wedge.

To deal with the water a garland is built of timber and clay immediately above the wedge and the water is collected in a series of 2 in. diam pipes which are taken vertically down through the base-plate on which the wall is built. At intervals of 14 ft vertically removable doors 14 in. in height are provided in the backsheeting to

give access to the back of the lining. As concreting proceeds the annular space between the backsheeting and the ground is filled with gravel. The final operation consists in injecting the annulus with cement grout under pressure when sufficient time has elapsed for the concrete to set and harden. In each segment of the falsework plates

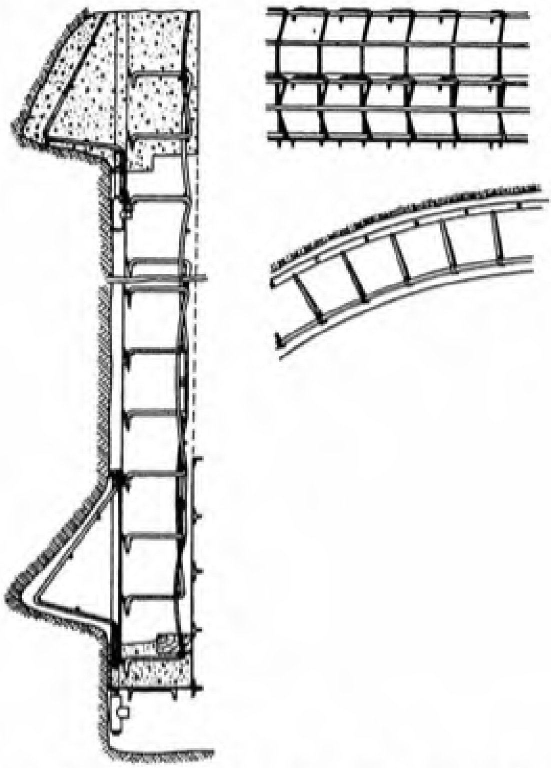


FIG. 205. DIAGRAM SHOWING R.C. SHAFT LINING BACKSHEETS (ATHERTON)

is a hole $1\frac{5}{8}$ in. diam against which a $1\frac{1}{2}$ in. diam pipe of length (when fitted with a coupling) equal to the thickness of the wall is placed and held by a tightly screwed union coupling through the plate (Fig. 206).

In shutting off the residual water a start is made at the lowest point i.e. at the pipe coming out of the temporary garland. Before coupling the cement milk under pressure to this through a flexible hose, an iron bar is driven through the pipe or pipes immediately above in order to burst the corrugated sheeting so that when the pipe or pipes leading out of the temporary garland are closed, the water can find its way

out through the row above. The injection of cement milk is then begun, all the cocks on the lowest row being closed. Pumping is continued without stopping until the cement shows that it has reached

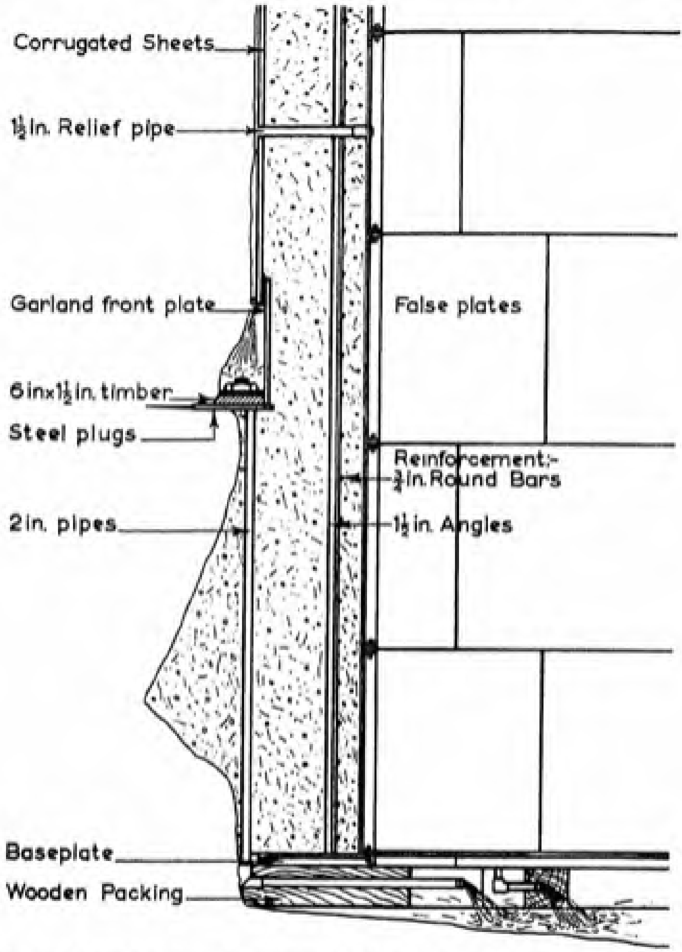


FIG. 206. BACK SHEETING, TEMPORARY GARLAND AND REINFORCED WALL

the next row of pipes. The cock on the pipe being injected is then closed, the sheets at the back of the third row above are punctured and injection started on the second row. This proceeds until a final seal is made where the two walls join. The degree of sealing off is high, leakage amounting to only ¼ gal/min on a 500 ft length of a

13 ft diam shaft and $1\frac{1}{4}$ gal/min from a 450 ft length of a 15 ft diam shaft.

The No. 1 downcast shaft at Calverton Colliery near Nottingham was sunk through the heavily-watered Bunter Sandstones commencing in 1937. A Sulzer sinking pump was installed to deal with the make of water of a maximum quantity of 1,000 gal/min from a depth of 600 ft. The actual water-bearing measures were first encountered at a depth of 20 yd and continued until a depth of 120 yd was reached. The shaft is 18 ft 2 in. in diameter and was sunk to the Top Hard seam at a depth of 560 yd. The shaft is lined with reinforced concrete walling 18 in. thick in the water-bearing strata and 14 in. thick in the dry strata. The total make of water after the sinking was completed was only 3 gal/min showing that the cementation process had been successful.

QUESTIONS

1. At the site of a proposed sinking there is a thickness of 80 ft of unconsolidated strata overlying the rock head. Discuss the available methods of sinking the shaft of finished diameter 18 ft to firm strata, and indicate how the choice of method is governed by the precise nature of the surface deposits.
2. Distinguish between the drop shaft and Caisson methods of shaft sinking. Indicate the types of deposits to which they are applicable.
3. Describe with diagrams the Honigmann system of sinking.
4. A shaft is to be sunk on the coast. There is 30 ft of drift clay, then a 100 ft of soft water-bearing strata containing seawater overlying the rock head. Explain generally how you would get through to the rock head.
5. Describe the boring operations which must precede sinking by the freezing process. Mention the special precautions which are required in these operations.
6. Distinguish between English and German forms of cast iron tubbing for shafts. Indicate the relative merits of these forms of permanent support. Describe concisely how a ring of underhung tubbing would be inserted.
7. Describe the chief items of plant and equipment to be installed at a sinking where the freezing system is to be adopted and give an outline of the various stages of this special method of sinking.
8. Under what conditions would the cementation system of shaft sinking be adopted? Describe the system giving an account of any pre-treatment of the ground which may be carried out and its purpose.

CHAPTER XV

DEEPENING AND WIDENING SHAFTS AND DRIVING STAPLE SHAFTS

DEEPENING A SHAFT

In the execution of this operation the method adopted depends largely on the conditions obtaining, in the same manner that it affects that of widening a shaft. If the shaft is required for no other purpose or only for ventilation purposes, sinking may simply be resumed below the sump and proceed in much the same manner as that adopted in sinking the initial depth. The changes required are the erection of a headgear, winding engine and scaffold winch and means of disposing of the debris if these do not already exist, or the addition of a central pulley for the sinking hoppet and the debris disposal arrangements if winding equipment is already installed, the existing pulleys being utilized for the scaffold ropes.

Where, however, deepening must proceed while the original shaft is still used for winding, means must be provided to transfer the debris from the sinking to the normal transport system and protection must be afforded to the sinkers from material falling down the shaft, unless the operations proceed on different shifts. In this case the scaffold ropes for the bricking scaffold may be led from the winch down the sides of the shaft and deflected to their correct position in the sinking by pulleys below the original pit-bottom. The sinking hoppet may be hoisted in the sinking by means of a tail-rope attached to one of the cages. The hoppet is then swung to one side in the pit-bottom or detached and removed to a convenient position near the pit-bottom, in both cases being emptied into a train of empty tubs or mine cars which are, on the other shift or shifts, wound out in the normal way with the coal and emptied on the surface along with any other debris from the mine. A centre-line and radius rod are used in the normal manner to ensure alignment of the sinking with the original shaft.

The arrangements generally adopted are to bore in the sump a hole in the centre of the shaft from which a centre line may be hung to ensure alignment. A short drift is driven (Fig. 207), to connect a convenient site in the pit-bottom a short distance from the shaft to the borehole and leave sufficient strata below the original shaft to protect the sinkers below. A small hoisting winch is erected to wind the hoppet in the shaft over a pulley erected on frames over the top

of the sinking and two further pulleys and winches to control the bricking scaffold. Alternatively, the hoisting engine may be erected on girders at the top of the sinking, the roof of the end of the drift being ripped to give the necessary height. Sinking proceeds in the normal manner, the contents of the hoppet being discharged down a chute into empty tubs in the drift which are hauled by a small winch to a track branching from the pit-bottom sidings.

When the sinking has reached the required depth and the lining has been completed and a pit-bottom has been constructed, the short

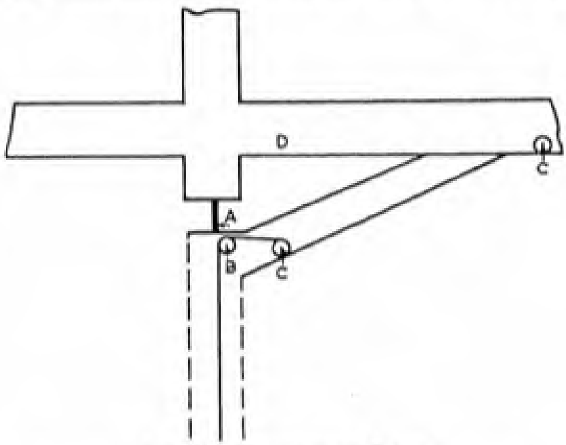


FIG. 207. DEEPENING A SHAFT

A, Locating Borehole; *B*, Hoisting Pulley; *C*, Hoist; *D*, Pit-bottom.

length of strata between the top of the sinking and the sump of the original shaft is removed by raising, i.e. sinking upwards. Occasionally shafts are deepened entirely by raising, the correct starting position having been determined by a very careful survey. The method is similar to that employed in raising a staple shaft.

STAPLE SHAFTS

Staple shafts are required in the following circumstances—

1. To connect seams above or below to main haulage roads in another seam.

2. In the horizon system of mining to connect roads in a seam with main cross-measure drivages, laterals or cross-cuts below.

3. To transfer output from a higher level to a pit-bottom at a lower level, coal winding facilities, pit-bottom sidings and other facilities having been transferred from the higher to the lower level when an increasing output from the latter justified this.

Spiral chutes are generally adopted for lowering coal from a higher to a lower level with minimum breakage and ladders or a cage, or both, must be provided for men. When coal is to be raised a compressed air, or preferably, an electric winding engine and cages or a cage and a balance weight are required (Fig. 208).

Staple pits may be sunk in the same manner as a main shaft and may be either rectangular or circular in shape, but some 90 per cent are raised as the debris descends by gravity and is delivered into tubs

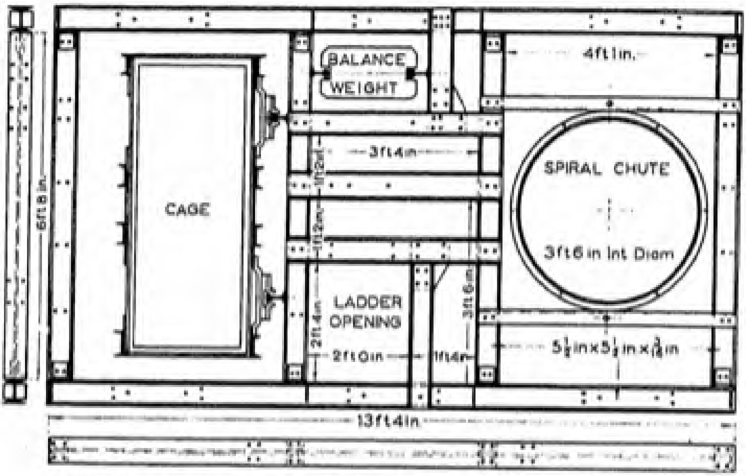


FIG. 208. ARRANGEMENTS IN STAPLE SHAFT IN A DUTCH COLLIERY

by a chute without handling and the rate of advance is generally higher. On the Continent and in this country a spiral chute is often installed which is first used for debris and afterwards for coal.

Circular Staple Pit

The method which may be adopted is shown in Fig. 209 which shows the arrangements at Harton Colliery, Co. Durham, to raise a staple shaft 11 ft in diameter 74 ft from the Bensham to the Yard seam. To take the weight of the stack 5 yd of concrete walling, 5 ft in thickness, was put in on each side of the centre line of the shaft and carried four girders, 16 in. by 6 in. and 27 ft in length, supporting the 6 ft width of the stack, and 9 ft above ground level. A layer of wooden baulks 6 in. in thickness was laid on top of these girders to form a floor seal but leaving a compartment 3 ft by 2 ft at each side in which plumb lines were suspended from a builder's lath over two $1\frac{1}{2}$ in. pipes 8 ft apart grouted into the floor; from which a centre line was

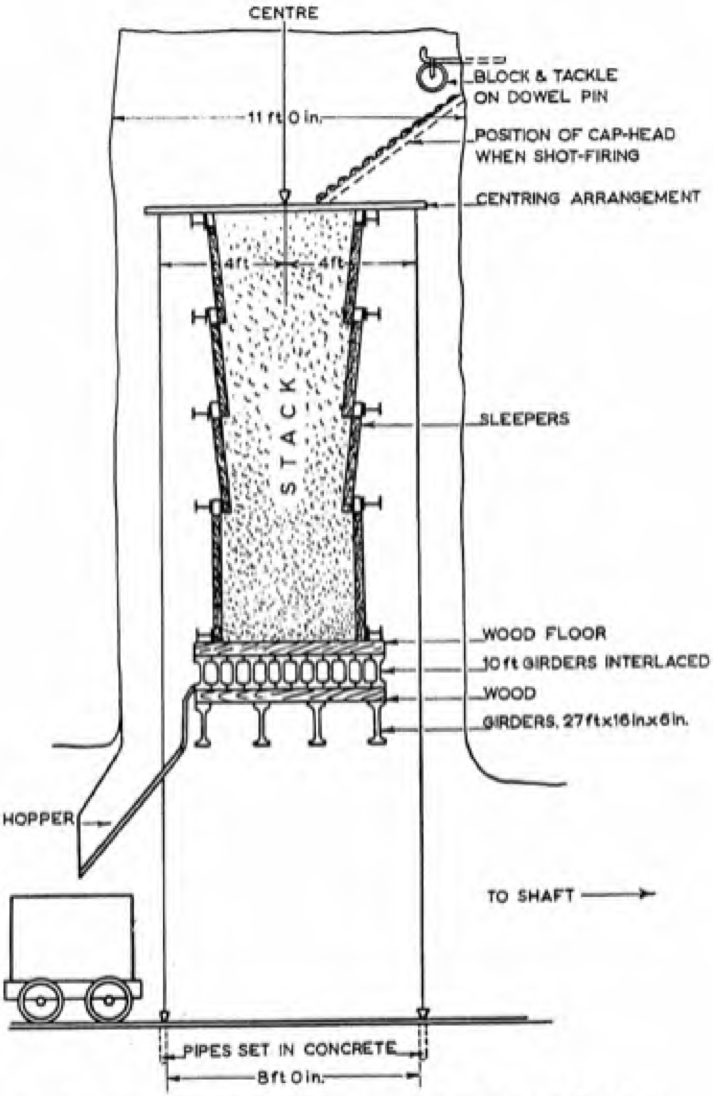


FIG. 209. METHOD OF RAISING A STAPLE PIT AT HARTON COLLIERY (N.C.B. BULLETIN)

transferred to the roof of the shaft as shown. One side of the stack was used for excess dirt which fell into the hopper shown, while the other side was used as a manway. On top of the baulks, girders 10 in. by 5 in. and 10 ft in length were interlaced, so that one end was let into the side and over these a further timber floor was laid.

The excavation took place in lifts of 3 ft girders being set across the shaft at this interval, with the space between the webs of the sets filled with sleepers and the centre filled with broken debris, thus forming a platform for drilling, firing and cleaning up broken rock. The work proceeded on two shifts each of two men, setting of supports and centring on the day shift and drilling and firing on the night shift, twenty-five to twenty-eight holes being drilled and sheathed; Polar Ajax being used as the explosive in charges of 12, 8 and 4 oz. A cap head was provided to deflect the debris from the manway.

A false floor of timber supported by 12 ft girders was put in at a height of 40 ft to take the weight above off the concrete walls. When the Yard seam was reached a pulley 2 ft in diameter was erected to lift the spiral chute segments and the stack was emptied. No lining was required in the strong rock penetrated. A similar staple shaft, 60 ft in length was raised at Horden Colliery where the cost of sinking and lining was £41 9s 4d per yard, the shaft being lined with 14 in. of brickwork.

Rectangular Staple Shaft

This shape is commonly adopted on the Continent, the arrangements at Laura Colliery, raised 130 yd, are similar to those shown in Fig. 210. The spiral chute was used for debris removal into tubs in the level below, the flow being controlled by a chute door. Support was by means of a series of rectangular steel frames at one metre intervals with twelve 8 in. square hardwood props between frames. The frames were supported in 50 ft lengths by letting the short sides into the walls of the shaft. The shaft was ventilated by a range of 20 in. diam sheet steel pipes protected by a perforated cap and supplied by a 10 h.p. forcing fan.

The cage compartment was protected by a safety platform to prevent men falling down when working and when firing. A platform of 6 in. by 6 in. baulks on four girders was used to receive the debris when shotfiring and to deliver it to sloping platforms which deflect to the spiral chute. A wooden working platform was provided for drilling and frame assembly. The rate of advance was 3¼ ft per day with two men in the shaft and one at the bottom dealing with tubs and supplies.

A similar system was adopted at Bradford Colliery to raise a

rectangular shaft, 12 ft 10 in. by 10 ft 2 in., a distance of 170 yd. The cost for labour was £79 17s and of materials and stores £79

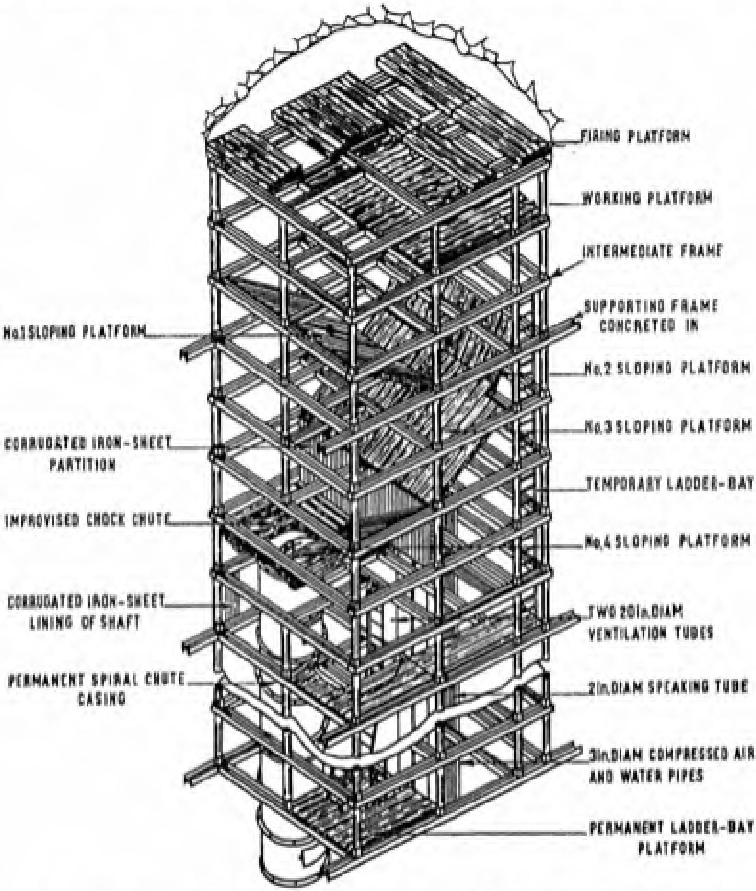


FIG. 210. METHOD OF RAISING RECTANGULAR STAPLE SHAFT (GODDARD)

10s 10d, total £150 7s 10d per yard and the rate of progress 2·91 yd per week.*

SHAFT WIDENING

The operation of widening a shaft may be necessitated by the decision to increase the output raised per shift or per day, in pursuance of a scheme of concentration; to increase the amount of

* GODDARD, C. L., "Modern practice in raising staple shafts," *Trans. Inst. Min. Eng.* Vol. III, p. 980.

ventilation or to reduce the pressure loss due to air friction in the shaft; or, where an old shaft is in disrepair, it is decided to increase the diameter and insert a new lining rather than repair and partially reline the old shaft.

The method adopted will depend upon whether the shaft can be taken out of use for winding and/or ventilation in which case it is usual to fill it with ashes, broken brick or timber, in fact any material which can be easily reloaded. The widening then proceeds as a normal sinking. If, however, ventilation must be continued (for example in the case of an upcast shaft which is not used for mineral or for men winding but is necessary for the ventilation of a colliery), the widening is generally carried out by means of a bell of steel plate which fits into the old shaft and extends some 3 ft above a working platform, with six key-bolts extending into the old shaft lining, from which the brickwork is stripped and the annulus between the old and the increased diameter of the shaft and the thickness of the new lining is excavated.

At the top of the bell is a grid through which the ventilating air passes. The bell and the working platform (Fig. 211), are suspended by four chains and ropes some 50 ft in length from a bricking or cementation scaffold designed to fit the new shaft diameter; this has doors in the centre to pass the hoppet when widening, but when lining, in stretches of approximately 60 ft, the doors are closed, the bell and the working platform lowered on to two girders across the old brickwork and secured there, and the four ropes and chains disconnected from the bricking scaffold. This also has grids of steel bars surrounding the doors and a narrow platform 1 ft 6 in. wide all round the scaffold. The concrete or the bricks and mortar for lining are delivered on to the doors. The temporary lining is removed and the concrete or brickwork inserted from the scaffold, which is raised by the scaffold winches through two ropes which carry the sinking hoppet rider (Fig. 211). Difficulty may be experienced from water and dust, picked up by the ventilating current, making visibility bad and working conditions difficult.

This method was used in enlarging the No. 3 Shaft at Mosley Common Colliery (*Smith*, "Shaft widening under difficult conditions," *T. I. Min. E*, Vol. 109, p. 280) from 12 ft to 22 ft in diameter and inserting a concrete lining, at first 18 in. and afterwards 12 in. in thickness. Where it is necessary to preserve winding facilities while shaft widening operations proceed it is necessary to confine these to periods when winding does not normally take place. The method generally adopted is similar to that just described but without the use of grids. A shield is designed to fit the old shaft as

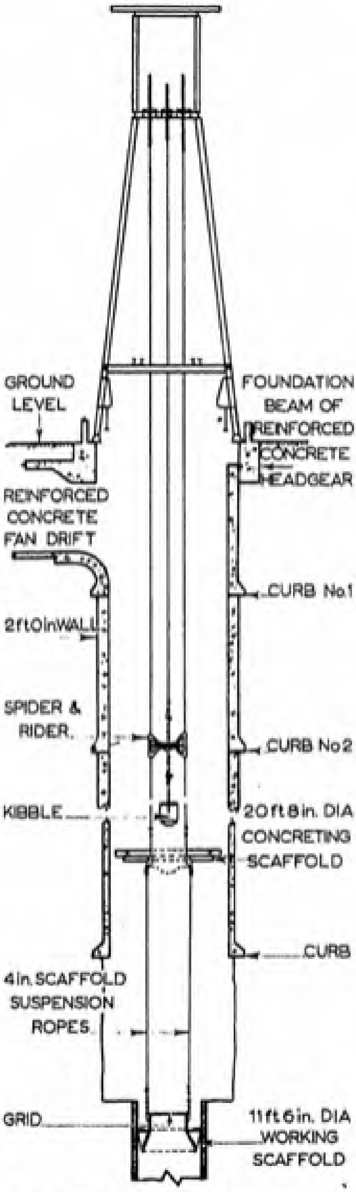


FIG. 211. METHOD OF WIDENING AN UPCAST SHAFT (SMITH)

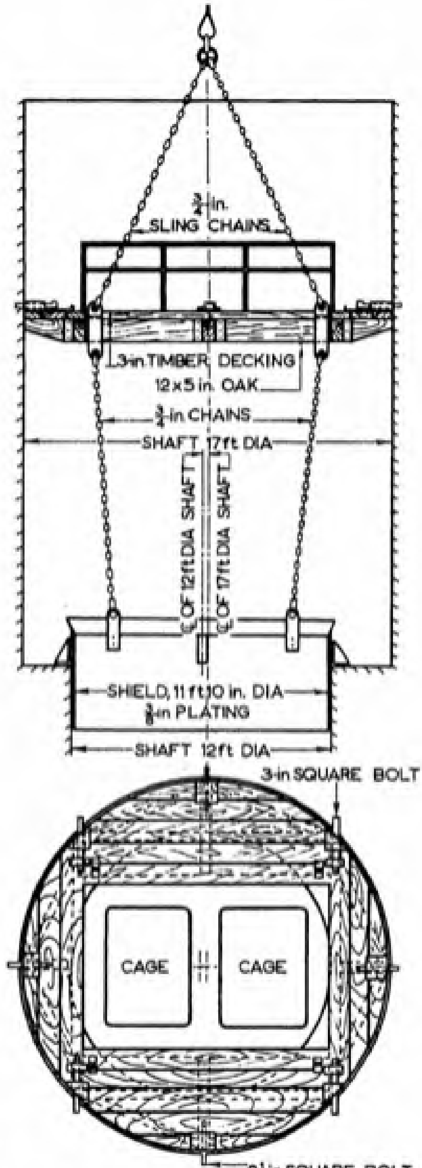


FIG. 212. BRICKING-SCAFFOLD AND SHIELD USED FOR WIDENING SHAFT (LATHAM)

closely as possible, allowing for any distortion of the old lining. The shaft illustrated (Fig. 212), at Cannock Wood Colliery, was originally 12 ft in diameter and was widened to 17 ft the depth being 200 yd. The shield was constructed of $\frac{3}{8}$ in. plating 11 ft 10 in. diam and 5 ft in height of which 2 ft 6 in. formed a fence. The shield was supported on the old shaft walling by four angle iron brackets (Fig. 212), and was attached to the bricking scaffold above by four $\frac{3}{4}$ in. chains and two $\frac{13}{16}$ in. ropes. The weight of the shield was 1·35 ton, that of the scaffold 1 ton.

When a sufficient length of the old shaft had been widened and temporarily supported, a bricking curb was inserted and the shield was lowered on to the old brickwork lining, the chains were disconnected and bricking of the new lining; carried out with the scaffold raised independently. The average rate of progress, excavating and bricking, was $4\frac{3}{8}$ yd per week. Winding was carried out on the day shift only, the remaining two shifts being devoted to widening.

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QUESTIONS

1. A shaft 13 ft in diameter lined with brick work has to be enlarged to 20 ft diameter.

Explain the method you would adopt (*a*) if the shaft is not in use, and (*b*) if the shaft is in use 12 hr each day for winding purposes and is fitted with rope guides.

2. A shaft 20 ft in diameter and 500 yd deep is to be deepened for winding from a depth of 700 yd. The shaft is in use for winding coal on two shifts and for materials on part of the third shift. The measures are strong and dry.

Describe how the operation of deepening could be carried out with the least possible interference with the present output.

3. To complete a planned scheme it is proposed to increase the size of an abandoned shaft from 14 ft to 20 ft diameter and deepen it from 450 to 650 yd. Give an account of a suitable method of carrying out this work.

4. Describe a suitable method of raising a staple pit through a distance of 150 ft dealing particularly with the methods used to ensure its verticality.

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